Chapter 2

Fabrication and Characterization Techniques

This chapter provides a description of several thin film deposition methods and electrical and analytical characterization techniques have been used to study the physical properties of high-k films as well as their interfaces with GaAs substrates in this dissertation. The principles of each technique will be briefly introduced along with a description of the instruments and settings used in this work.

2.1 Metal-Oxide-Semiconductor Capacitor Fabrication

2.1.1 GaAs Substrate Cleaning and Passivation

Preparation of a clean crystalline semiconductor surface under vacuum conditions remains to be one of the most challenging issues in III-V semiconductor technology. A semiconductor surface exposed to air is covered with native oxides which have to be removed in vacuum or in an inert atmosphere before any dielectric layer growth. One of the major drawbacks of the III-V semiconductors particularly GaAs has been the high number of surface state defects, and the technological inability to reduce them. Different types of passivation techniques both wet and dry have been investigated yet the search for a highly reproducible simple technique for GaAs passivation remains to be urgent.
Wet Chemical Surface treatment

The GaAs samples were chemically cleaned by trichloroethylene (TCE), Acetone and Methanol successively for 10 min each, followed by de-ionized (DI) water rinsed and high purity N₂ blow. Subsequently, Dilute HCl (HCl / DI water, 1:10) was used to etch the surface native oxide. The (NH₄OH) treatment is carried out by soaking the samples in (NH₄OH) (29%) solution for 3 min in room temperature to remove native oxide and rinsing in flowing de-ionized (DI) water followed by gently drying the surface using an N₂ blow. The (NH₄OH) etching step removes arsenic and gallium oxides from the surface and the surface becomes covered by elemental arsenic and a tiny amount of gallium sub-oxide [1].

Sulfur Passivation

Sulfide surface treatments involving the immersion of the GaAs wafer in Na₂S, (NH₄)₂Sₓ, (NH₄)₂S, and S₂Cl₂ solutions under specific conditions have been employed. It is believed that sulfidation of GaAs relies on the elemental forms of Ga and As binding with S to produce Ga-S and As-S bonds which are responsible for the passivation effects of GaAs [2, 3] These wet techniques have proven to be successful at reducing surface state densities, but issues with long term stability and reproducibility have resulted in some variation in the interpretation of experimental results [4-7]. To explain the mechanism of the wet sulfide passivation, sulfur bonding to both Ga and As at the same time at a low temperature (<250 °C), is commonly suggested [8]. At higher temperature, only Ga-S bond is conserved [9, 10], while As atoms at interface probably vaporize or exist in elemental state because GA-S bond has higher binding energy, more favorable (ΔGᵣ=-209 Kcal/mole for GaS) over As-S bond (ΔGᵣ=-168.6 Kcal/mole for As₂O₃) [11]. Moreover, As₂O₃ has high vapor pressure and much lower
melting point (~300 °C), which may account for decomposition or evaporation of $\text{As}_2\text{O}_3$ at higher temperature or in vacuum. Because annealing at elevated temperature or drying in vacuum shortly after the solution coating is a necessary step to get rid of water or other solvents, the dominance of Ga-S bond on passivated surface would a reasonable inference.

**Interfacial Passivation Layer: IPL**

The effectiveness of wet sulfide passivation has been proven by many research groups. However, the extent of the passivating effectiveness has great dependence of particular processing and physical condition of the film such as, thickness, coverage uniformity, annealing condition. To achieve uniform passivation effect, a thin layer up to a few monolayers is preferable. Sulfide solution also can introduce more serious contamination problem of GaAs than HF does on Si.

Degradation of the wet passivation effects can be prevented by deposition of a protecting interfacial passivation layers (IPLs) such as Si, germanium (Ge), and Si/Ge between dielectrics and GaAs. This interfacial passivation layer will act as a buffer layer between deposited dielectric and GaAs because of the close lattice match between Si, Ge or SiGe and GaAs. More specifically, the interlayer should:

1. Reduce interface state density,
2. Mitigate problems associated with interfacial Ga and As sub-oxides ($\text{Ga}_x\text{O}_y$, $\text{As}_x\text{O}_y$)
3. Prevent reactions and inter-diffusion at the GaAs-dielectric interface, and
4. Separate the inversion layer from the high-k dielectric to reduce remote coulomb and phonon scattering [12]

In principle, the composition of a deposited layer may be closely controlled and tailored to provide optimal interface characteristics. Interlayer suppress
crystallization of the overlying high-k dielectric, reduce Ga and As interdiffusion, improve capacitor C-V characteristic, and reduce midgap $D_{it}$ to reasonable levels ($\sim 1 \times 10^{12}$ cm$^{-2}$ eV$^{-1}$ [13]). However these interlayer also offer advantages, namely, higher dielectric constant, improved thermal stability, and reduced formation of Ga and As oxides during subsequent processing.

**Plasma Nitridation**

Adopting the technique of deposition of a thin interfacial passivation player (IPL) before dielectric deposition though improves device characteristics but it is well known that Si and Ge are amphoteric dopants for GaAs, and a thin layer of Si or Ge between the dielectric and GaAs may alter the doping concentration or even induce the counter doping of the GaAs substrate, causing the instability of the threshold voltage [14]. On the other hand, incorporation of nitrogen in the interfacial layer has been shown to be beneficial as the interfacial nitride acts as a diffusion barrier to GaAs and prevents excessive interfacial layer growth due to the oxidation of GaAs.

**2.1.2 RF Magnetron Sputtering**

Sputtering has become a widely accepted process for the deposition of thin films. Radio Frequency vacuum-based film deposition process can be used for deposition of a variety of films such as metals, alloys, metal nitrides, semiconductors and insulators [15]. The atoms of the desired material (known as target) are ejected by bombardment of energetic ions. The ejected atoms get deposited on the substrate. Since the atoms are transferred to the substrate by a mechanical process rather than chemical or thermal process, virtually any material can be deposited making universality a strong feature of the sputtering technique.
The principle of sputtering is based on the momentum transfer between the bombarding species and the target atoms [16]. Target atoms are placed at cathode where a negative bias is applied. The substrate is made anode. Plasma is generated by using an inert gas like argon. Positive ions of plasma strike the target atoms and cause momentum transfer. The target atoms are ejected and accelerate towards the substrate and get deposited. For efficient momentum transfer, weight of target species must be closely matched to that of the bombarding species. This means that Neon may be used to deposit light elements and argon for heavier elements. A magnetic field can be applied by using a magnetron behind the target material to enhance the sputtering yield. The magnetron creates a magnetic field to increase density of plasma near the target resulting in higher deposition rate at a lower power. In sputtering, a sputtering gas (usually argon) is introduced into a vacuum chamber where an applied voltage ionizes the argon gas. The newly formed Ar\(^+\) ions accelerate toward the negatively charged cathode, which is at the target material. When an ion approaches the target, there are five major interactions that can occur. It is illustrated in Figure 2.1.

Figure 2.1: Interactions with incident ions at the target surface [16].
Radio Frequency (RF) sputtering is used for dielectric film deposition because of electron oscillation with the ac field resulting in no charge accumulation at the target surface. The capabilities of sputtering and the availability of high purity targets and gases make sputtering a popular choice for the deposition of thin films [17].

Figure 2.2: Schematic diagram for RF magnetron sputtering system.

Figure 2.2 illustrates schematically the TECHNICS UHV RF-magnetron sputtering system used for deposition of Interfacial passivation layer (IPL) as well as dielectrics for all experiments in this dissertation. The system consists of two chambers: main chamber and loadlock chamber. Both the top and the bottom electrodes are shielded by guard rings. The diameter of the top electrode is 4 inch while that of the target electrode is 6 inch and the distance between them is 3 inch. The base pressure of the main chamber is maintained at lower than 5 x 10^{-6} Torr to limit the impurities inside the chamber to a minimal level. Three RF-magnetron guns are attached to the system on top of the main chamber. Both the top and the bottom electrodes are shielded by guard rings.
The diameter of the top electrode is 4 inch while that of the target electrode is 6 inch and the distance between them is 3 inch.

The material to be sputtered is made into a target and mounted onto a circular copper backing plate. In our case the targets consist of a circular disk of hot pressed 99.99% purity high-k (Si, HfO$_2$, La$_2$O$_3$, Y$_2$O$_3$, TiO$_2$ and Ta$_2$O$_5$) which is 6 inch in diameter and approximately 0.25 inch thick. During deposition, the samples are kept inverted and placed into substrate table facing the target. A manually controlled shutter separates the target and the substrate. This help prevent contamination of the target during sample loading and unloading, protect the sample during pre-conditioning as well as provide means of controlling high-k dielectric deposition thickness during sputtering. Ar, being a noble gas which does not react with either the target or the semiconductor wafer, is then introduced into the chamber at a specified pressure (~2 mTorr). The RF supply is then switched on and stabilized to the required power and induced d.c. bias levels; this bias is an indication of the sheath potential and is a good sign of the ion bombardment energy. During this time the substrate is shielded by the top shutter. Once preconditioning is complete, the top shutter is opened marking the beginning of the deposition process.

### 2.1.3 Rapid Thermal Annealing

Rapid Thermal Annealing (RTA) is a thermal process, often used for defects recovery or molecular introduction to dielectric thin films, for lattice recovery or impurity electrical activation of doped or ion implanted wafers. The annealing after deposition is considered to bring the suppression of leakage current because of the defects in the films and surface roughness. And this thermal process also exerts an influence on hysteresis and flat band voltage ($V_{FB}$).
In this experiment, Rapid Thermal Processing MILA-3000 from ULVAC is used for annealing deposited high-k dielectric thin films. Figure 2.3 illustrated the schematic drawing for MILA-3000. High purity gas ambience can be obtained by pumping out and purging with the in use ambient gas. This RTP system is heated-up by infrared lamp heating furnace and cooled-down by flowing water radiator. The furnace temperature is of the range from room temperature to around 1200 °C with ramp-up of less than 50 °C /sec and much slower on cooling-down. The available ambient gases are N\textsubscript{2} and O\textsubscript{2} at atmospheric pressure by keeping the flowing gas at the rate of 1 lt. /min.

2.1.4 Contact metallization by Thermal Evaporation

Perhaps the simplest technique for depositing a material in thin film form is by vacuum evaporation. In this process, the material to be evaporated is heated in an evacuated chamber so that it attains a gaseous state. Vapors of this material
traverse the space from the source to the substrate, on which they eventually land.

As the name implies, the heating is carried out by passing a large current through a filament container (usually in the shape of a basket), which has a finite electrical resistance (as shown in Figure 2.4). The evaporation temperature and its inertness to alloying/chemical reaction with the evaporant dictate the choice of this filament material. Here, we used tungsten filament baskets. This technique is also known as “indirect” thermal evaporation since a supporting material is used to hold the evaporant. Once the metal is evaporated, its vapor undergoes collisions with the surrounding gas molecules inside the evaporation chamber. As a result, a fraction is scattered within a given instance during their

Figure 2.4: Schematic diagram of Hind Hivac thermal evaporation System.
transfer through the ambient gas. The mean free path for air at 25 °C is approximately 45 and 4500 cm at pressures of $10^{-4}$ and $10^{-6}$ Torr, respectively.

Therefore, pressures lower than $10^{-5}$ Torr are necessary to ensure a straight-line path for most of the evaporated species and for substrate-to-source distance of approximately 40 cm in a vacuum chamber. Good vacuum is also a prerequisite for producing contamination free deposits [18, 19]. Metal deposition rates of 0.5 µm/min are typically desired in vacuum evaporation. This necessitates that the equilibrium pressure of the evaporant be in the $10^{-6}$ Torr range, and restricts the use to materials which can be evaporated from heated crucibles. Materials such as aluminum and gold are nearly ideal for this technique. On the other hand, materials such as tungsten and titanium have extremely low vapor pressures, and cannot be delivered in this manner.

For MOS test capacitors fabrication, contact metallization was made by evaporated circular Al dots having two different of area $1.96 \times 10^{-3}$ cm$^2$ and $2.5 \times 10^{-4}$ cm$^2$ through a shadow mask in our experiment.

### 2.1.5 Ohmic contact formation by D.C. sputtering

Sputter deposition, or sputtering, is a versatile technique, and is extensively used in the deposition of thin films in microcircuit technology. The reasons for its popularity are (a) the ability to deposit a wide variety of metals and insulators, as well as their mixtures, (b) the replication of target composition in the deposited film, and (c) the capability for in situ cleaning of the substrate prior to film deposition. The need for alloys with stringent stoichiometric limits, conformal coverage, and better adherence, for magnetic and microelectronic materials, increased the demand for sputtering deposition. Some of the benefits of sputtering include:
1. High uniformity of thickness;
2. Good adhesion of film to substrate;
3. Reproducibility of films;
4. Ability to deposit and maintain the stoichiometry of the target material;
5. Relative simplicity of thickness control.

Figure 2.5: Schematic of the DC Sputtering Chamber.

In DC sputtering, a sputtering gas (usually argon) is introduced into a vacuum chamber where an applied voltage ionizes the argon gas. The newly formed Ar\(^+\) ions accelerate toward the negatively charged cathode, which is at the target material. When an ion approaches the target, there are five major interactions that can occur.

Figure 2.5 shows this situation, where multiple electrons reach the anode and the Ar\(^+\) ions reach the cathode. At sufficiently high applied voltages, some of these Ar\(^+\) ions can eject secondary electrons from the cathode, thus adding to the supply of electrons which contribute to the avalanche multiplication process. This can eventually lead to gaseous breakdown [20] with the current being
limited by the circuit impedance. For this condition, $\text{Ar}^+$ ions bombard the cathode, resulting in sputtering of its surface material by momentum transfer. In addition, secondary electrons emitted at the cathode participate in sustaining the discharge by ionizing collisions with argon molecules.

2.2 Characterization Methods

This section provides a brief description of the analytical characterization methods used for materials characterization of high-k dielectrics and interfaces in the experiments in this dissertation.

2.2.1 X-ray photoelectron spectroscopy

X-ray photoelectron spectroscopy (XPS), also known as electron spectroscopy for chemical analysis (ESCA), is a quantitative spectroscopic technique that yields information on the electronic structure, elemental composition and chemical state in the near surface region (< 5 nm) of a material. It has its origins in the discovery of the photoelectric effect by Hertz, was given a more precise energetic description by Einstein and was further developed in the work by Robinson and Rawlinson of X-ray photoelectron spectra for different metals. Later, Siegbahn, et al. developed XPS into a sensitive, high resolution method for the determination of the binding energy of the electrons for which he was eventually awarded the Nobel Prize [21-24]. Today XPS is a standard technique capable of providing valuable information about the electronic structure, the chemical composition and the stoichiometry near the surface of the sample.
XPS spectra are obtained by irradiating a material in vacuum with a beam of soft X-rays while simultaneously measuring the kinetic energy and number of electrons that escape from the top several atomic layers of the material being analyzed. XPS requires ultra-high vacuum (UHV) conditions. During analysis, the pressures of chambers that were used in this work were in the 10^{-9}-10^{-10} Torr range. Figure 2-6 shows the schematic drawing of the primary XPS system used in this study.

Photons in the x-ray range of the spectrum can have energies as high as 10 keV and when allowed to interact with atoms will interact with orbiting electrons primarily via a conventional photon absorption process [25]. Both monochromatic aluminum K-alpha x-rays (1486.7 eV) and non-monochromatic magnesium K-alpha x-ray (1253.6 eV) is commonly used. Typically, monochromatic aluminum x-rays have better energy resolution (0.4-0.6 eV) than non-monochromatic magnesium x-rays (0.9-1.0 eV). For much higher energy resolution, high-intensity, narrow-energy-width synchrotron radiation, is used. If
the photon energy is higher than the binding energy of core electrons in a material, the photons can interact with it and generate a photoelectron. Only those electrons originating from the surface, or a few atomic layers below, can escape from the surface to reach the detector and contribute to an XPS peak. Electrons that scatter on their way out of a solid contribute to the broad secondary electron background. Since the mean free path of electrons in solids is very small, most of the detected electrons come from the top 5 nm of the sample. This makes XPS a surface-sensitive technique for chemical analysis [26].

Figure 2.7: Energy-level diagrams showing the electron transitions in XPS.

Figure 2.7 illustrates the electronic transition involved in XPS. First, an electron is ejected from one of the core electronic levels by an incident X-ray photon. The kinetic energy $KE$ of the emitted core electron as measured by the instrument is:

$$KE = h\nu - BE - \phi$$

Where, $h\nu$ is the energy of the incident X-ray photons, $BE$ is the binding energy of the atomic orbital from which the emitted electron originates, and $\phi$ is the work function of the spectrometer.
Because each element has a unique set of binding energies, XPS spectra can be used to identify and determine the concentration of the elements in the surface. The binding energy of a core-level electron depends also on the surroundings of the atoms. Variations of binding energies for an element in different chemical compounds can arise for various reasons such as: difference in the oxidation state, difference in the molecular environment, different lattice parameters, etc. Binding energy shifts due to these effects are usually called chemical shifts and can be used to identify the chemical oxidation states of the materials being analyzed [27]. The binding energy shift can be expressed in the following equation:

\[
\Delta BE = BE - BE_0 = IA + EA
\]

Where, \(BE_0\) is the binding energy of the core-level electron in the isolated atom. The intra-atomic part \(IA\) can be described in terms of the effective charge of the atom in a molecule or crystal as \(IA=Kq\), where \(K\) is a constant for the chemical element. The extra-atomic part \(EA\) is the potential energy produced by the surroundings. This part is often referred as Madelung potential. Identification of chemical states of an atom can be made from the exact measurement of the peak positions and their chemical shifts.

### 2.2.2 Time of Flight Secondary Ion Mass Spectroscopy

In secondary ion mass spectroscopy (SIMS), an energetic beam of focused ions is directed at the sample surface in a high or ultra high vacuum (UHV) environment. The transfer of momentum from the impinging primary ions to the sample surface causes sputtering of surface atoms and molecules. Some of the sputtered species are ejected with positive or negative charges; these are termed secondary ions. The secondary ions are then mass analyzed using a double
focusing mass spectrometer or energy filtered quadruple mass spectrometer. This method can be used to acquire a variety of information about the surface, near surface, or bulk composition of the sample, depending on the instrumental parameter. If the rate of sputtering is relatively low, a complete mass spectrum can be recorded to provide a surface analysis of the outermost 5 nm of the sample. This is often termed as static SIMS. Alternatively, the intensity of one or more of the peaks in the mass spectrum can be continuously recorded at a higher sputtering rate to provide an in depth concentration profile of the near-surface region. Finally, a secondary ion image of the surface can be generated to provide a spatially resolved analysis of the surface, near the surface, or bulk of the solid. Ultimate depth resolution (<1 nm) is required for characterizing ultra-thin layers and thus the lowest possible primary ion energies and/or maximum glancing angles of incidence must be used.

Figure 2.8: Schematic depiction of SIMS source region.

Primary beam species useful in SIMS include Cs+, O2+, O, Ar+, and Ga+ at energies between 1 and 30 keV. Primary ions are implanted and mix with sample atoms to depths of 1 to 10 nm. Sputter rates in typical SIMS experiments vary
between 0.5 and 5 nm/s. Sputter rates depend on primary beam intensity, sample material, and crystal orientation. The sputter yield is the ratio of the number of atoms sputtered to the number of impinging primary ions. Typical SIMS sputter yields fall in a range from 5 and 15.

2.2.3 Atomic Force Microscopy

Atomic force microscopy (AFM) is a type of scanning probe microscopy and is useful for determining the topography of surfaces [28]. It uses a sharp probe to scan across a surface while the interactions between the tip and the sample are monitored. The observations of surface roughness were made using tapping mode AFM (easyScan 2 from Nanosurf). Tapping mode AFM (TM-AFM) enables to measure surface morphology in high resolution depended on size of cantilever. These probes have a typical resonance frequency of 325 kHz and force constant of 40 N/m. The scanning area size is 10 μm × 10 μm. In this study, the resolution limit is below 1 nm.

Figure 2.9: A schematic diagram of an AFM system.
Figure 2.9 shows the schematic drawing of typical commercial AFM equipment. As the cantilever approaches the sample, the force between the cantilever edge and the atoms of the sample surface cause the cantilever to bend. The laser and photo diode are used to detect the bending of the cantilever which gives information of the height of the tip above the surface. The cantilever is controlled by a z-direction feedback circuit while a topographic image of the surface results from scanning in the x and y directions.

There are three primary modes of operating an AFM: contact mode, noncontact mode, and tapping mode. Tapping mode was used for this work. In tapping mode, the cantilever is vibrated by a piezoelectric device, and the probe makes only limited contact to the sample during part of the vibrational cycle. Tapping mode often enables one to measure surface morphology with higher resolution than the other modes, and minimizes damage done to the sample [29].

To determine the roughness of a sample, an image of the surface is obtained by scanning in the x and y directions. The surface roughness is evaluated by the values of $R_{MAX}$ the difference between the maximum and minimum height values of the surface and the root mean square (RMS) roughness. The standard deviation of the height values within a given scan area is given by:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} (Z_i - Z_{ave})^2}{N}}$$

Where $Z_{ave}$ is the average Z value within the given area, $Z_i$ is the current Z value, and N is the number of points within a given area.

AFM measurements should always be performed with high quality, durable, sharp tips. Worn tips produce completely different images and the roughness information obtained is not reliable. One should also take care to avoid multiple tip imaging.
2.2.4 Transmission Electron Microscopy

The Transmission Electron Microscopy (TEM) is a useful technique for examining the cross section of the metal gate/high-k dielectric stack. In TEM imaging, an electron beam is focused on the sample by means of electromagnetic lenses. Since the wavelength of the electron beam is less than that of visible ray, the resolution of TEM is higher than optical microscope [30].

The sample thickness must be thin enough so that the electron beam can get transmitted through the sample. Therefore, special sample preparation is required. Generally, high resolution TEM (HR-TEM) combines phase contrast from elastic scattering events and mass-thickness contrast from inelastic scattering. A TEM equipped with the image filter can filter out inelastic scattered electrons for high resolution (HR) images. Therefore, image filtered HRTEM provides almost pure phase contrast, which shows better crystallographic structures, planar defects and strain field information at the atomic scale [31].

However, for samples with multiple amorphous layers, where the contrast can only come from mass thickness contrast, HRTEM is not sufficient to investigate those layers and image-filtered HRTEM is even worse. Z-contrast in Scanning TEM (STEM) mode can overcome the issues with phase contrast HRTEM imaging since a fine beam is scanned across the sample in a raster manner similar to conventional scanning electron microscopy (SEM). During the scan scattered high angle, low angle, and surface secondary electron signals are collected using high angle angular dark field (HAADF), low angle ADF (LAADF), and Everhart-Thorley detectors. In HAADF mode the elastic Bragg scattering is reduced so the image strongly depends on the sample mass providing good compositional and chemical contrasts in atomic scale. HAADF images are called Z-contrast images. Samples for TEM imaging in the experiments were prepared by using FEI Quanta 200 3D Focused Ion Beam (FIB)
system. HR-TEM imaging was performed using a high resolution transmission electron microscope (HRTEM), model JEOL 2100 operating at 200 kV.

Figure 2.10: Schematic cross section of TEM.

2.2.5 Electrical Characterization Methods

This section discusses the two most commonly used methods for electrical characterization of metal-oxide-semiconductor structures. Capacitance-voltage and current voltage are two terminal measurement techniques that are used to extract information about the dielectric and semiconductor properties and determine important device parameters.
Capacitance-Voltage Characterization
The capacitance–voltage (C–V) method is a common measurement performed on MOS devices to determine many important parameters related to metal gate, gate-dielectric and semiconductor substrate. The C–V measurements for all experiments in this work were done using Agilent B1500A semiconductor parameter analyzer. When a dc bias overlapped with an ac signal is applied to the two terminals of a MOS structure, the capacitance and conductance can be measured simultaneously. It is noted that the superimposed ac signal should be as small as possible so that the measurement is not affected or altered by the ac signal [32]. By sweeping the gate bias the capacitance of the MOS capacitor varies as \( C = \frac{dQ}{dV} \). Information extracted from C-V measurement includes dielectric equivalent oxide thickness, semiconductor doping density, and flatband voltage.

Current-voltage Characterization
The current–voltage (I–V) measurement is commonly used for characterization of MOS devices to analyze the quality of the dielectric film and investigate the dielectric breakdown and reliability properties. The current conduction through the dielectric occurs through a quantum mechanical process called tunneling. For SiO₂, there are two types of well known tunneling mechanisms which are called Fowler–Nordheim (FN) tunneling and direct tunneling (DT) [33]. If carriers tunnel through a triangular potential barrier, then FN tunneling process is dominant and the relationship is given by:

\[
J_{Fn} = A_G E_{ox}^2 \exp\left(-\frac{B}{E_{ox}}\right) \quad \text{where,}
\]

\[
A = \frac{q^3}{8\pi h} \left( \frac{m}{m_{ox}} \right) \quad B = \frac{8\pi \sqrt{2m_{ox}\Phi_B^3}}{3qh}
\]
The FN tunneling current increases exponentially with applied field. If the current conduction occurs through a trapezoidal barrier, then the direct tunneling process is dominant and the relationship is given by:

\[
J_{DT} = A_G E_{OX}^2 \exp \left( -B \left[ 1 - \frac{q V_{OX}}{\Phi_B} \right]^{\frac{1}{2}} \frac{E_{OX}^{\frac{1}{2}}}{E_{ox}} \right)
\]

The current conduction is complicated in high-k gate dielectrics since high-k films deposited by atomic layer deposition typically have traps and defects that contribute to carrier conduction through the dielectric. Frenkel-Poole (FP) emission and trap assisted tunneling have been reported as carrier conduction mechanisms in high-k dielectrics resulting in an increase in the total gate current [34]. FP currents are due to the field enhanced excitation of electrons through trapping sites in the dielectric. These current conduction mechanisms have stronger temperature dependence than quantum mechanical tunneling processes and can be distinguished by means of I-V measurements performed as a function of temperature [35].
References


