Radiation Response of Al$_2$O$_3$ based Metal-Oxide-Semiconductor Structures under Gamma-ray

Man DING

The College of Energy and Electrical Engineering, Hohai University, Nanjing, Jiangsu, China

*corresponding author’s e-mail: farry3386@163.com

Abstract. The radiation effect in aluminium oxide based MOS capacitors is studied in this article. The radiation induced oxide and interface trapped charge characteristic as well as the leakage current and charge transportation mechanism are studied by using Capacitance-Voltage and Current-Voltage measurements. The results show that the radiation induced oxide and interface trapped charges are both positive with the density in the order of $10^{12}$ cm$^{-2}$ which increase with the increase of irradiation total dose, the charge transport is dominated by Schottky mechanism and the leakage current as well as the trap barrier height rarely change after irradiation. This provides a reference for the application of Al$_2$O$_3$ based MOS devices in space environment.

1. Introduction

Microelectronic technology has been developing according to ‘Moore’s Law’ for the past decades, and the feature size of transistors has been shrinking to micrometre, sub-micrometre, deep and very deep sub-micrometre. The developing roadmap of semiconductor industry issued by ITRS specifies the size of the transistors especially the size reduction of complementary metal-oxide-semiconductor (CMOS) devices. Therefore, the advanced CMOS technology requires scaling down of the gate length, channel width and gate thickness, and the traditional gate materials cannot make it anymore.

SiO$_2$, which is widely used as the gate material in traditional MOS devices, is not applicable in advanced MOS devices, as the leakage current and static power consumption would increase dramatically when the thickness of SiO$_2$ decrease to that lower than 2nm which would seriously impact the properties of MOS devices. Alternative materials with larger permittivity which can be called high-k materials have been proposed to replace SiO$_2$ as the gate dielectric such as HfO$_2$, Al$_2$O$_3$, ZrO$_2$, La$_2$O$_3$[1]. High-k gate dielectrics used in MOS devices should not only have large permittivity but also have large band gap and band offset with silicon substrate to inhibit the charge tunnelling through the dielectric/silicon interface, and the dielectric/silicon interface must also have high thermodynamic stability to avoid the formation of silicates on the interface and good performance in electrical property with low interface trap density.

Al$_2$O$_3$ has been proposed as a candidate to replace SiO$_2$ as the gate dielectric of MOS devices as the dielectric constant (~8.9) and band gap (~8.7eV) are both larger than that of SiO$_2$, this provides a small equivalent oxide thickness in MOS devices and large enough valence and conductance band offsets between the gate dielectric and silicon substrate so that a sufficiently high electron and hole barrier on the interface and a low leakage current.

Many researchers have studied the application of Al$_2$O$_3$ used as gate dielectrics in MOS devices, but few is focused on the radiation effect of Al$_2$O$_3$ based MOS devices which is important for...
electronic devices working in space environment. The deposition temperature and thermal annealing effects on the electrical characteristics of atomic layer deposited Al$_2$O$_3$ films on silicon was studied in[2]. The interface/border traps characterization in Al$_2$O$_3$/AlN/GaN structures were derived by dynamic capacitance dispersion technique in[3-5]. The charge trapping and passivation properties of Al$_2$O$_3$ based stack gate dielectric under gamma-ray irradiation was studied by using Capacitance-Voltage and Deep-Level Transient Spectroscopy measurements in[1,6,7]. The radiation induced defect characteristic as well as the leakage current in Al$_2$O$_3$ based metal-semiconductor-oxide structures under Si heavy ion were studied in[8], the charge trapping property and charge transportation mechanism in Al$_2$O$_3$ were investigated and the origination of the leakage current and capacitance decrease were also obtained in this work. Except for gamma-ray and Si heavy ions, the radiation hardness of atomic layer deposited Al$_2$O$_3$ gate insulator in GaN-based MIS HEMTS under proton irradiation was also studied in[9]. Existing studies mostly focused on the electronic properties including the radiation induced charge trapping and leakage current characteristics, the failure mechanism of Al$_2$O$_3$-based MOS structures under irradiation were rarely studied physically or chemically which can give us a deeper understanding of radiation induced charge trapping and leakage current.

This paper studies the radiation induced charge generation, charge trapping and charge transportation in Al$_2$O$_3$ based MOS structures. The Al$_2$O$_3$ films were prepared on silicon substrate by atomic layer deposition method, and the radiation induced trapping charge density in Al$_2$O$_3$ and on the Al$_2$O$_3$/Si interface were measured by high frequency Capacitance-Voltage (CV) method and calculated by Terman method, the leakage current characteristic and the charge transportation mechanism through Al$_2$O$_3$/Si structure were studied by current-voltage (IV) measurement method and related analysis. Study of the electronic characteristic of the Al$_2$O$_3$ based MOS structures before and after different total dose of gamma-ray irradiation is helpful for us to understand the failure mechanism of high-k dielectric based MOS devices working in space.

2. Experiment
2-inch p type silicon with the resistivity of 1-3 Ω·cm and the crystal orientation of <100> is used as the substrate. Al$_2$O$_3$ film is deposited on the silicon substrate by ALD method by using Trimethyl aluminium (TMA) and H$_2$O as the precursor. The thickness of Al$_2$O$_3$ film is measured to be 14.1nm by ellipsometer. The film is annealed by rapid thermal annealing (RTA) process under 450 °C for 60s after deposition to strengthen the film cohesion and diminish the number of defects, and then Al$_2$O$_3$/Si structure is formed. For one chip with Al$_2$O$_3$/Si structure, aluminium is thermally evaporated through a hard mask to form dot electrodes with the diameter of 60μm on the surface of Al$_2$O$_3$ film, and it is also evaporated on the bottom of silicon substrate to form the bottom electrode, and these Al/Al$_2$O$_3$/Si structures are then annealed through RTA process under 300 °C for 60s to form ohmic contact for CV and IV measurements. The chips with Al$_2$O$_3$/Si or Al/Al$_2$O$_3$/Si structures are divided into four equal parts and each part is irradiated by gamma-ray with different total doses. $^{60}$Co gamma-ray with the total dose of 1.2Mrad/2.5Mrad/4Mrad in the rate of 100rad/s is used to irradiate the Al$_2$O$_3$ based MOS structures. The electronic properties of about 10 numbers of Al$_2$O$_3$/Si and Al/Al$_2$O$_3$/Si samples are measured by CV and IV methods before and after each total dose of gamma-ray irradiation. The radiation induced charge generation, charge trapping and charge transportation characteristics are analysed from the experimental results to help us understanding the damage characteristics of the Al$_2$O$_3$ based MOS structures.

3. Experimental results
3.1. Radiation induced charge trapping characteristic
We used Keithley 4200 SCS to measure the CV characteristic of Al/Al$_2$O$_3$/Si MOS capacitor with the voltage ranging from -2+1V by the interval of 0.05V, and the normalized CV curves before and after different total dose of irradiation are shown in Figure 1. The capacitance value in the accumulation
zone of the CV curve is $1.485 \times 10^{-9}$F so that the relative permittivity of the ALD Al$_2$O$_3$ thin film in this paper can be derived to be 8.368 which is close to the theoretical permittivity of Al$_2$O$_3$.

From Figure 1, we can see that the CV curves shift to the negative voltage direction and show a stretch-out after irradiation, illustrating that charges were generated and trapped and formed oxide and interface trapped charge in Al$_2$O$_3$/Si structure after gamma-ray irradiation, and negative shift of CV curve means positive oxide trapped charges. The oxide and interface trapped charge densities in Al$_2$O$_3$ bulk and Al$_2$O$_3$/Si interface were calculated by using Terman method and the results are shown in Figure 2 and Table 1.

**Figure 1.** CV curves of Al/Al$_2$O$_3$/Si structures before and after irradiation.

**Figure 2.** Oxide and interface trapped charge density in Al/Al$_2$O$_3$/Si structure.
Table 1. Oxide and interface trapped charge density in Al/Al$_2$O$_3$/Si structure.

| Radiation total dose (rad) | Oxide trapped charge density (cm$^{-2}$) | Interface trapped charge density (cm$^{-2}$) |
|---------------------------|----------------------------------------|------------------------------------------|
| 1.2M                      | 4.87×10$^{11}$                         | 1.86×10$^{12}$                           |
| 2.5M                      | 9.44×10$^{11}$                         | 3.65×10$^{12}$                           |
| 4M                        | 1.82×10$^{12}$                         | 4.43×10$^{12}$                           |

The radiation induced oxide and interface trapped charges in Al$_2$O$_3$/Si structure are both positive in the order of 10$^{11}$-10$^{12}$ cm$^{-2}$ and they both increase with the increase of irradiation total dose. Gamma-ray with the average energy of 1.25 MeV can ionize the atoms and generate electron-hole pairs inside the gate dielectric of MOS structures, some of the electron and holes would compound with each other, some of them would be swept out of the dielectric layer under local electrical fields, and other charges would be captured by the trapping centres in the structure in the process of their transportation through the dielectric layer under electrical field to form oxide and interface trapped charges. New defects would also generated and act as new trapping centres in this process. Larger total dose gives birth to larger number of electron-holes pairs and more trapping centres which is the reason for the increasing oxide and interface trapped charge density with the increasing of irradiation total dose.

Indeed, the number of the radiation induced trapped charge density is not only dependent on the charge yield under radiation but also dependent on the trapping capacity of the dielectric material which can be expressed by the value of effective trapping efficiency of the gate dielectric as shown in (1).

$$ f_{ot} = -\frac{\Delta V_{mg} \varepsilon_{ox}}{q \kappa_g f y_{eq} t_{phys} D} $$

where, $f_{ot}$ is the effective trapping efficiency, $\Delta V_{mg}$ is the radiation induced midgag shift, $\varepsilon_{ox}$ is the permittivity of SiO$_2$, $q$ is electronic charge, $\kappa_g$ is the electron-hole pair generation per unit dose in Al$_2$O$_3$ which is the known value of charge generation in SiO$_2$ ($\sim$8.1×10$^{12}$ cm$^{-3}$·rad$^{-1}$ in [10]) scaled by the ratio of the bandgap of SiO$_2$ to the bandgap of Al$_2$O$_3$, $f_y$ is the charge yield in SiO$_2$ in the same electrical field ($\sim$0.3 in [11]), $t_{eq}$ is the equivalent oxide thickness, $t_{phys}$ is the physical thickness of Al$_2$O$_3$, $D$ is the radiation total dose.

The effective trapping efficiency of the ALD-Al$_2$O$_3$ in this paper is 11% under 1.2 Mrad irradiation, which is lower compared with the effective trapping efficiency in SiO$_2$ reported in [5] ranging from a few percent up to 50%, which is dependent primarily on the number of oxygen vacancies in the oxide. This result shows that the radiation induced charge trapping in ALD-Al$_2$O$_3$ is not critical as that in SiO$_2$ and it is a favourable candidate as gate dielectric in MOS devices working in space environment.

3.2 radiation induced leakage current characteristic of Al$_2$O$_3$/Si structure

The leakage current characteristic of the Al$_2$O$_3$/Si structure was measured by using Keithley 4200SCS, and the leakage current under the applied voltage of +1 V is in the order of 10$^{-6}$ A which changes little after gamma irradiation. The charge transport mechanism through the dielectric is dependent on the magnitude of applied electric field, with ohmic current at low fields shown in (2), and Schottky or Pool-Frenkel current at high fields shown in (3)-(7).

Ohmic current:

$$ J = \sigma E $$

(2)

Where, $J$ is the current density, $\sigma$ is the electrical conductivity and $E$ is the electric field.

Schottky current:

$$ J = A T^2 \exp[-(\phi - \beta_{sch} E^{1/2})/kT] $$

(3)

$$ \beta_{sch} = (\varepsilon^3/4\pi\varepsilon_0\varepsilon_r)^{1/2} $$

(4)

$$ A = \frac{4\pi q(m^*)^2k^2}{\hbar^2} = 120(m^*/m_0) $$

(5)
Where, $A$ is Richardson constant defined in (5), $m^*$ is the electron effective mass. $T$ is Kelvin temperature, $\Phi$ is the barrier height, $\beta_{sch}$ is a constant related with dielectric constant defined in (4), $k$ is Boltzmann constant, $e$ is the electron charge, $\varepsilon_0$ is vacuum permittivity, $\varepsilon_r$ is the relative dielectric constant.

Poole-Frenkel current:

$$J = J_0 \exp[-(\Phi - \beta_{PF} E^{1/2}) / kT]$$  \hspace{1cm} (6)

$$\beta_{PF} = (e^3 / \pi \varepsilon_0 \varepsilon_r)^{1/2}$$  \hspace{1cm} (7)

Where, $J_0$ is the initial current density without electric field.

As $\beta_{sch}$ and $\beta_{PF}$ are constants that only dependent on the relative dielectric constant of the material, they help to determine the charge transport mechanism in Al$_2$O$_3$ as shown in Figure 3.

![Figure 3. Charge transport mechanism in Al/Al$_2$O$_3$/Si MOS structure.](image)

Here, the charge transport mechanism is dominated by Schottky emission both at gate injection and is determined by both Schottky and PF emission at substrate injection, implying that the gate leakage current is influenced by the Al/Al$_2$O$_3$ interface barrier, and the substrate leakage current is influenced not only by the Al$_2$O$_3$/Si interface barrier but also by the barriers inside Al$_2$O$_3$. This implies that the leakage current is influenced by the interface barrier between the hafnium oxide and the silicon substrate. On the other hand, the corresponding barrier height is figured out from the charge transport mechanism and it shows no obvious change after irradiation.

4. Conclusion

The damage effect of gamma-ray irradiation on the ALD-Al$_2$O$_3$ based MOS structures is studied in this paper, and we can draw the following conclusions:

1) The dielectric constant of Al$_2$O$_3$ film is 8.368 in this paper which is very close to the theoretical Al$_2$O$_3$ permittivity, implying that the ALD method is an ideal fabrication method for Al$_2$O$_3$ based MOS devices.

2) The radiation induced oxide and interface trapped charge in Al$_2$O$_3$/Si structure are both positive with the density of up to 10$^{12}$cm$^{-2}$, which increase with the increase of irradiation total dose. And the effective trapping efficiency in Al$_2$O$_3$ is 11%, which is lower than that in traditional SiO$_2$ gate dielectric.

3) The leakage current through Al$_2$O$_3$ changes little after gamma-ray irradiation, and the charge transport is dominated by Schottky emission mechanism and the interface barrier height also shows no obvious change after irradiation.

To sum up, the ALD-Al$_2$O$_3$ based MOS structures are radiation resistant with low radiation induced trapped charge and little variance of leakage current from the aspect of electronic properties. However,
the physical and chemical structure and their performance evolution under total dosage irradiation cannot be neglected which may also limit the application of Al₂O₃ based MOS devices in space environment.

References
[1] Cao S, Ke X, Ming S, et al. 2019 J. Mater. Sci.-Mater. El. 30 11079-85
[2] Rafi J M, Zabala M, Beldarrain O, et al. 2011 J. Electrochem. Soc. 158 G108-14
[3] Liu S H, Yang S, Tang Z K, et al. 2015 Appl. Phys. Lett. 106 051605-1
[4] Hori Y, Yatabe Z and Hashizume T 2013 J. Appl. Phys. 114 244503-1
[5] Ma X H, Zhu J J, Liao X Y, et al. 2013 Appl. Phys. Lett. 103 033510-1
[6] Chen Z, Dong P, Xie M, et al. 2019 J. Mater. Sci.-Mater. El. 30 1148-52
[7] Spassov D, Paskaleva A, Davidovic V, et al. 2019 Proc. IEEE Int. Conf. on Microelectronics (Nis, Serbia) p 59
[8] Zhang J, Chen X, Wang L, et al. 2019 J. Appl. Phys. 125 115701-1
[9] Chang S J, Cho K J, Jung H W, et al. 2019 Ecs J. Solid. State Sc. 8 Q245-8
[10] Benedetto J M and Boesch H E 1986 IEEE Tran. Nucl. Sci. 33 1317-23
[11] Schwank J R, Shaneyfelt M R, Fleetwood D M, et al. 2008 IEEE Tran. Nucl. Sci. 55 1833-53