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Properties of Radiation Induced Interface States and Positive Charges in MOS Structures

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Properties of the radiation induced positive charges(Not) and the Si-SiO_2 interface states(Dit) are discussed. Experimental results of MOS devices oxydized in different conditions are discussed by analyzing the voltage shifts into the Not and the Dit. Correlation between the Dit and the Not are also shown. The mechanisms of the radiation induced positive charge buildup and the Si-SiO_2 interface states generation will be discussed.

1.Introduction

The positive charge buildup in the oxide and the Si-SiO_2 interface states generation in MOS structure by ionizing radiation such as gamma ray and X ray are well known. MOS structures are most fundamental structure of Si integrated circuits and it is necessary to understand the basic mechanisms of charge trapping in the oxide and in the Si-SiO_2 interface to develope the radiation hardened devices for the space.

The positive charge buildup is interpreted as follows. Electron-hole pairs are created in the oxide of by ionizing radiation. Some of the pairs recombine and the rest of them are separated by the oxide field. Electrons are transported to the metal or silicon and holes move slowly because of large mobility difference between electrons and holes [1].
The generation mechanism of the Si-SiO_2 interface is interpreted that holes transported from the oxide to the interface break SiH and SiOH bonds at the Si-SiO_2 interface [2].

The radiation induced positive charges were revealed as E' center and the Si-SiO_2 interface states were also revealed as Pb center at the Si-SiO_2 interface by using ESR [3]. E' center was an unsaturated trivalent Si bonded with three oxygen atoms, Pb center was an unsaturated trivalent Si bonded with other Si atoms, which were first observed by Nish et.al by ESR measurement [4]. These traps are closely related with oxidation process, and the generation probability of traps by irradiation is concerned to the stress [5], weak bonds of Si-Si, Si-O [6] and the existence of SiH and SiOH at the Si-SiO_2 inteface [7].

Generally, devices are irradiated to Co-60 gamma-ray to know the radiation hardness. The radiation induced positive charges are estimated by mid gap voltage shift or flat band voltage shift from C-V measurement. Some workers reported the negatively shifted flat band voltage by irradiation turned to positive as time passed [8] [9]. VFB shift should be produced by the positive charges and negatively or positively charged interface states density which are distributed from mid gap energy to Fermi energy. In this work, the

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process dependency of radiation effects on MOS structures are investigated and correlations between radiation induced positive charges ,and the Si-SiO_2 interface states density and the mechanisms of radiation induced traps are also discussed.

Figure 1 shows a C-V curves shift before and after irradiation. The net positive charges in the oxide can be estimated from the difference of mid gap voltage between these two curves. The midgap voltage condition is the midgap energy level equals the Fermi level at the silicon surfaces.

Figure 2 shows correlations between experimental ΔVmg- ΔVFB and the integration of negatively charged interface states from the mid gap(Ei) to the Fermi level(EF) of MOS capacitors with oxide thickness 37~82 nm.

2.Experimental results

MOS structures used in this work were fabricated on n type 3~6 Ωcm, <100> oriented silicon substrates. Dry oxides were grown to thicknesses of 37~100 nm at 1000 ℃ and 1100℃, in pure O_2 or in O_2 diluted by Ar or N_2. Postmetal annealing (PMA) was done at 400℃ in nitrogen or in hydrogen for 10 min to 90 min. MOS samples were irradiated up to a total dose of 1 Mrads(Si). Radiation indused positive charges (ΔNot) and generated Si-SiO_2 interface states (ΔDit) increase as oxygen content decreases in oxidation atmosphere as shown in Fig.3. MOS capacitors oxidized in Ar diluted oxygen is small compare to the case of N_2 diluted oxygen.

Figure 4 shows annealing time dependency of ΔDit and ΔNot after Co-60 gamma ray irradiation for capacitors with PMA H_2 and N_2. Dit and Not values before irradiation are same order. ΔNot depends on PMA time, and it becomes smaller as annealing time increases in N_2. On the contrary, Not increases as annealing time becomes longer in H_2.

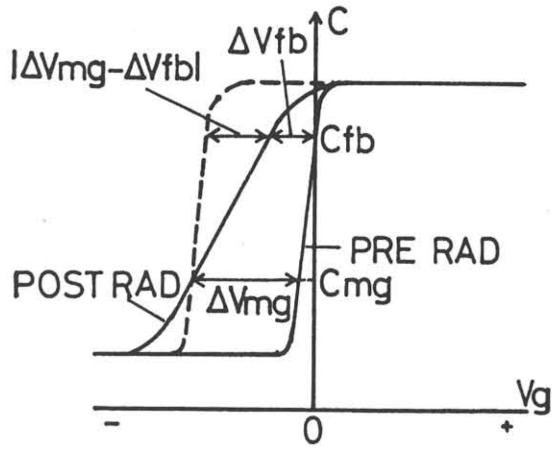

Fig.1 Relation between a flat band volltage shift(ΔVFB) and a mid gap voltage shift(ΔVmg) on C-V characteristics.

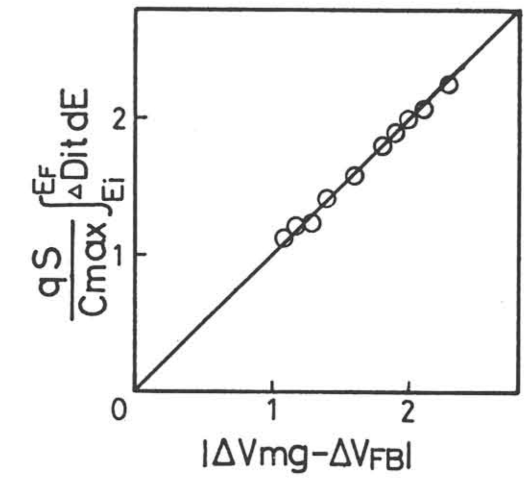

Fig.2 Correlation between the voltage corespond to the interface states charges integrated from a mid gap energy level to Fermi level and $|\Delta$ Vmg-Δ VFB $|$ in experiment.

Figures 5 is replotted the increased Dit versus positive charge buildup by Co-60 gamma ray irradiation from Fig. 3 , the gradient of ΔDit to the increase of ΔNot is around 0.75 and does not change with the partial pressure.

Figure 6 shows the ratio between the radiation genarated Si-SiO_2 interface states (ΔDit) and the radiation induced positive charge buildup(ΔNot) in regard to the oxide thickness for PMA in N_2 and in H_2 at 400℃ for 30 min, in which all oxide films are grown in dry O_2 at 1000℃, follwed by N_2 annealing at the oxidation temperature.

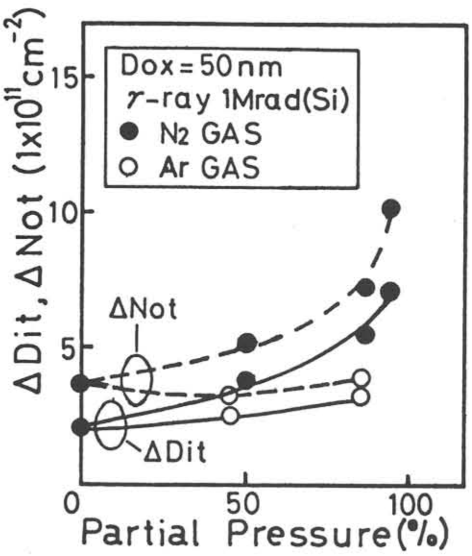

Fig.3 Radiation induced positive charges (ΔNot) and generated Si-SiO_2 interface states(ΔDit) in MOS capacitors oxidized in oxygen diluted by Ar or N_2.

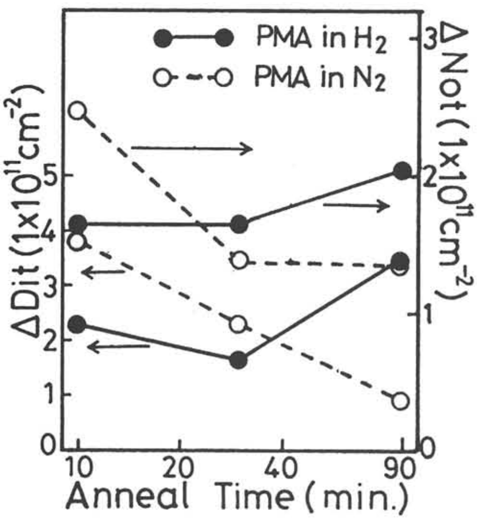

Fig.4 Annealing time dependency of ΔNot and ΔDit after Co-60 gamma ray irradiation for capacitors with PMA hydrogen and nitrogen.

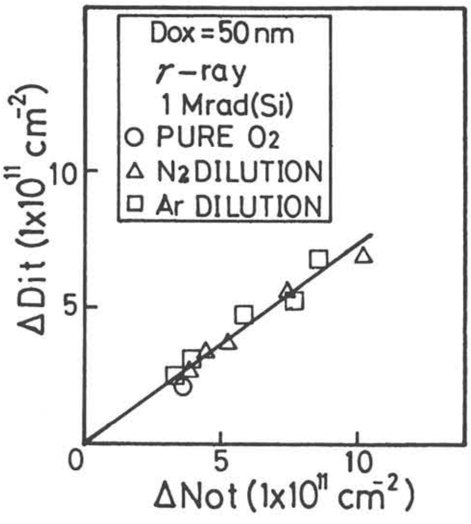

Fig.5 ΔDit against ΔNot in diluted Oxide.

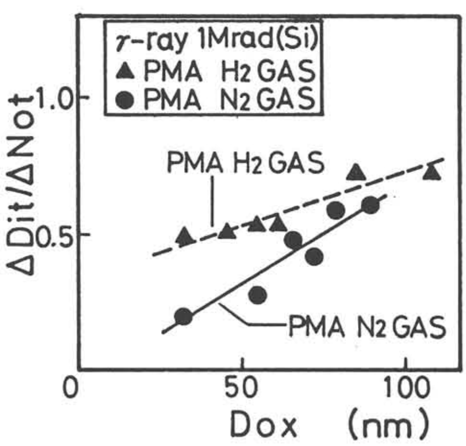

Fig.6 The ratios between ΔDit and ΔNot of MOS capacitors PMA in H_2 and in N_2 against oxide thickness, PMA in H_2 and in N_2.

3.Discussions

The Si-SiO_2 interface states have amphoteric character and it can be charged positively or negatively [10]. The interface states positioned in the lower half of the band gap are donorlike states and the interface states in the upper half of the band gap are acceptorlike states which are generally accepted .[11][12][13] The interface states levels can be predictable from the theoretical investigation. The Si-Si weak bond at the interface forms continuous states below midgap and that the interface states level changes with bond distance and the Si-O weak bond forms continuous states above midgap where the states level also changes withbond distance.[14] We can see the role of H to the radiation effects in the oxide. Hy-drogen atoms can penetrate into the oxide during oxidation and break the weak bond easily at the Si-SiO_2 interface, and it also terminates the dangling bond at the surface forming Si-H bond. PMA decreases the weak bonds and forms Si-H bonds in the oxide and decrease the Dit.

ΔDit and ΔNot in MOS capacitor oxidized in N_2 dilution are larger than the oxidized in Ar dilution as shown in Fig.3. The reason is due to hydrogen content in gases used, which is contained as H_2O : 2.58ppm in Ar and 5.34ppm in N_2.

We consider the interstitial hydrogen atoms exist throughout the bulk oxide as excess hydrogen atoms. Interstitial hydrogen atoms are activated easily by the energy of gamma rays and act to break Si-H and Si-OH bonds, producing Pb center at the $Si\text{-}SiO_2$ interface as follows.

$$\begin{aligned} &Si{\equiv}Si\text{-}H+HO\text{-}Si{\equiv}O+nHi+Rad \\ &\qquad Si{\equiv}Si\cdot + H_2 \quad \text{(Pb center)} \\ &\rightarrow \; Si{\equiv}Si\text{---}O\text{-}Si{\equiv}O+H_2 \quad \text{(weak bond)} \\ &\qquad OH\text{---}Si{\equiv}O \quad \text{(weak bond)} \end{aligned}$$

Hydro-oxide Si can be broken by gamma ray irradiation, and Si-O-Si bonds can be broken by interstitial hydrogen atoms activiated by gamma rays, producing the E' center as a hole trap.

$$\begin{aligned} &O{\equiv}Si\text{-}O\text{-}Si{\equiv}O+Hi+Rad\text{-}O{\equiv}Si\cdot + OH\text{-}Si{\equiv}O \\ &O{\equiv}Si\text{-}OH+Rad\text{-}O{\equiv}Si\cdot + OH \\ &O{\equiv}Si\text{-}H+Rad\text{-}O{\equiv}Si\cdot + H \\ &O{\equiv}Si\cdot + h\text{-}O{\equiv}Si \quad \text{(E' center)} \end{aligned}$$

The ratio between ΔDit and ΔNot is constant as shown in Fig. 5. Generated holes transport to $Si\text{-}SiO_2$ interface, and break the hydrogen bond within $O{\equiv}Si\text{-}H$ at $Si\text{-}SiO_2$ interface. Holes are captured in Si dangling bond as follows.

$$O{\equiv}Si\text{-}H+h\text{-}O{\equiv}Si\cdot +h+H^0\text{-}O{\equiv}Si \; +H^0$$

Released hydrogen H^0 has higher energy than the stable condition, it diffuses throughout the oxide and to the $Si\text{-}SiO_2$ interface producing Pb center by breaking Si-H bond as follows.

$$Si{\equiv}Si\text{-}H+H^0\text{-}Si{\equiv}Si\cdot +H_2 \quad \text{(Pb center)}$$

So, the generated ΔDit is directly proportional to ΔNot. It is thought that the increase of the ratio between ΔDit and ΔNot against the oxide thickness in Fig.6 originated from the strain at the $Si\text{-}SiO_2$ interface depends on the oxide thickness, in addition to hydrogen effect.

4.Conclusion

(1)Good correlation between the charges of the Dit integrated from midgap to Fermi-level, and the difference between the midgap voltage shift (ΔVmg) and the flat-band shift(ΔVFB) was found. This is very practical method to analyze the oxide charge from C-V measurement.

(2)Hydrogens make the MOS structure more sensitive to ionized radiation. Especialy, interstitial hydrogen atoms can be activated easily by irradiation.

(3)The strain at $Si\text{-}SiO_2$ interface increases the radiation effect in MOS structures.

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