Total dose effect in NMOS devices

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ABSTRACT. When electronic components work under irradiation condition, total dose effect would be engendered. In order to weaken total dose effect on components, the author set NMOS transistor which are a section of the components as an example to study on the principle of the production process of total dose effect as well as the influence on the working NMOS devices.

1 GENERAL INSTRUCTIONS

Integrated circuit is a key element in controlling nuclear equipment in space crafts which is easily influenced by the irradiation. As a result, anti-irradiation technology becomes increasingly pronounced. Among the many types of irradiation, total dose effect is one of the most important which would effects electric characteristic parameters in MOSFET [1], including threshold voltage drifting [2], turn-off current increasing and mobility decreasing [3]. All of the abovementioned parameter may cause permanent or temporal damaged. As a consequence, further study in total dose effect becomes a magnitude field of search.

Up to now, the study of total dose effect can be divided into four periods on the basis of different hotspots:

1) Total dose effect was found in 1964, during the first period from1964 to 1976. Scientist mainly studied the process of the transformation of charges in SiO_2.

Derbenwick as well as his partner found that electron-hole pairs are produced in oxide materials and that reducing the thickness of oxide is a potent method to reduce the threshold voltage drift amount.

2) During 1977~1985, scientists focused on the key defects and impurities. Based on the data, oxygen vacancy is hole- traps in oxide and P_b defect is the interface state.

3) During 1986~1997, studies was on a topic that MOS devices changes during irradiation and degradation after irradiation. Also, scientists developed ways to test anti-irradiation strengthen methods which improved space crafts' performances.

Positive charges return to be neutral and threshold voltage drifting less.

4) From the year 1998 to now, hot topics switched to theoretical modeling and ultrathin oxide research. The development of computers helped a lot to macroscopic effect and microscope theory of total dose effect.

Because of the superiority MOS device possesses, the research on total dose effect has more practical significance.

This paper mainly discusses from radiation environment, total dose effect irradiation principle, to the effect of total dose effect to NMOS, as following Figure 1 showed.
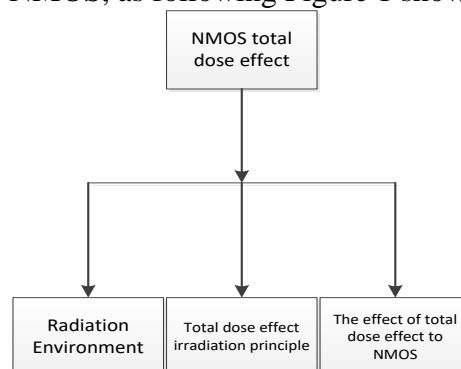

Figure 1 The structure of this paper

2 RADIATION ENVIRONMENT

Space radiation environment has influence on all sorts of space crafts, such as artificial earth satellite, space stations, spacecrafts, especially the electronic systems (components) in space crafts. The electronic devices of the surface and the internal of the space crafts are impacted by radiation effect. Ionization damages and displacement damage have great influence on the electronic system on the surface, while the ionization damage and displacement damage have little influence on the inner of spacecrafts, for they have to undergo single event effect (SEE). The radiation environment of external space in atmosphere includes: galactic cosmic rays, solar cosmic rays, solar wind and protons as well as electrons in earth radiation belt.

Galactic cosmic rays refer to some high-energy charged particles which are temporal equivalent and hard to shield from outer solar system. However, the radiation flux is low; Solar wind refers to a constant charged particle (proton and electron) current. The space where low-energy plasma and charged particle move, dominated geomagnetic field is called magnetosphere. The plasma belt in the magnetosphere usually has no radiation damage on electronic components, but may have noise effect on electronic system.

Earth radiation belt is also called Allen radiation belt. It refers to high-energy charged particle radiation field captured by earth magnetic field which includes: 1) Inner radiation belt locates between 600km and 8000km which is made up of high-energy protons. The low-energy particle's center position is far from the earth while the high-energy particle locates near the earth. Outer radiation belt locates between 4800km and 35000km which is mainly made up of protons and electrons. Because the protons possess low energy, outer radiation belt is virtually electron belt. 2) Artificial radiation belt is almost artificial electrons belt. It is produced by high altitude nuclear explosion. The radiation environment is caused by nuclear explosion 'Starfish' in 1962. Up to now, the intensity of it can be neglected. 3) Natural radiation belt is natural formed radiation belt in the space environment.

Total dose effect is an important part of the space radiation effect on electronic system. As a result, this essay mainly studies on the influence of total dose effect.

3 TOTAL DOSE EFFECT IRRADIATION PRINCIPLE

3.1 *Produce ionization charge*

The concentration where electron-hole pairs are produced is proportional to the energy which transformed from radiation particle to target material. The lost of energy in a unit length of one particle is called barrier energy. It is the function of the mass of one particle and the density of target material. The energy which one particle transformed to target material through interacting with the target atom is the total dose effect it produced. The unit of it is rad.
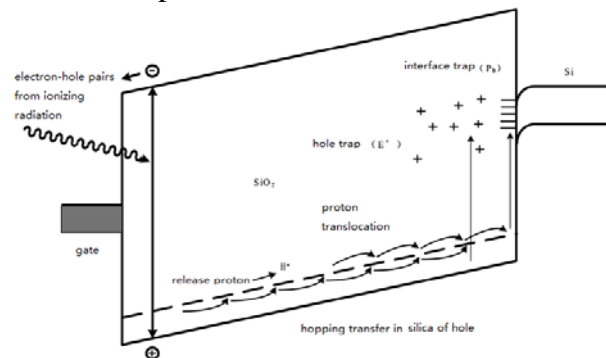

Figure2 Radiation produced trapped charges and interface state

As Figure2 diagram shows, from the appearing of electron-hole pairs produced by ionizing to ionization defect, five steps are happening: 1, electron-hole pairs production→2, electron-hole pair's combination→3, free carrier transformation in oxidative horizon→4, carrier captured by trap, trapped charges appear →5, carriers interact with proton, interface trapped appear.

During the process 1, the particle energy Eion to stimulate every electron-hole pairs only relates to target material which determines the production rate **g** of electron-hole pairs with the density of the material ρ .

$$g_0 = \frac{\rho \cdot D(= 1rad)}{E_{ion}}$$ （1）

After the production of electron-hole pairs, some parts of them combine immediately (process 2). The ratio of pairs which did not combine to the total amount is called the production rate f_y, which is the function of radiation type and electric field.

$$f_y = \left(\frac{|E| + E_0}{|E| + E_1}\right)^m$$ （2）

In the oxide, the mobility of electrons is higher than that of holes, so oxide layer is easily produced by electric field. The rest of holes transform through hopping in the shallow level trap (process 3). Deep level trap in the medium can capture some holes while they are transforming, called the fixation of positive charged in oxide layer (process 4). However, some parts of captured holes' trap exchange electrons with Si near the interface because of tunneling effect. This happens between holes and defects containing and would causes interface traps （process 5）.

3.2 *Oxide-trapped charge*

Oxide-trapped charges could show electropositive, because their generation is from neutral oxygen vacancies capturing holes. Then the neutral oxygen vacancy defects emerge, as the E' centre in Figure2.The majority holes transforms in shallow level traps in SiO_2. Deep level traps are widely distributed in oxide layer and most of them locate near the boundaries

Both of the traps can exchange charges with Si near the interface. The distance from traps to boundaries determines the ability of exchange charges. An E' center that can capture and release holes rapidly is called border trap or exchange state which usually locate 3nm from Si-SiO_2 interface. Some of them who possess deep level and far from the interface can also capture and release the carriers; however, the probability is on low level. As a consequence, deep level traps can be regarded as the center of capture and fixed charges which are oxide fixed positive charges.

Oxide fixed positive charges N_{ot} have significantly effect on components and circuits' dc characteristics. The most important of the effects is to drive the threshold voltage negatively drift ΔVot in NMOS and PMOS. To the NMOS device, this kind of drift let the threshold voltage decrease while negatively increasing in PMOS.

$$\Delta V_{ot} = -\frac{t_{ox}}{\varepsilon_0 \varepsilon_{ox}} q \Delta N_{ot}$$ （3）

Along with gate oxide thickness reduced, the drift amount of threshold voltage reduced. This is because

$$-\Delta V_{ot}(\Delta N_{ot}) \propto t_{ox}^2$$ （4）

It is obvious to see that reduce the thickness of medium can reduce the drift amount of threshold voltage remarkably. For this reason, positive charges invested in thicker oxide field became a difficult point in anti-irradiation technology. Positive charges in oxide field make Si in NMOS became substrate inversion, forming leakage tunnel. As graphic Figure3 shows, L is the length of pipeline；W is the width of pipeline. Before the irradiation, when it is shut down, current only flows through gate oxide. On the contrary, after the irradiation, part of fixed positive charges invests under gate

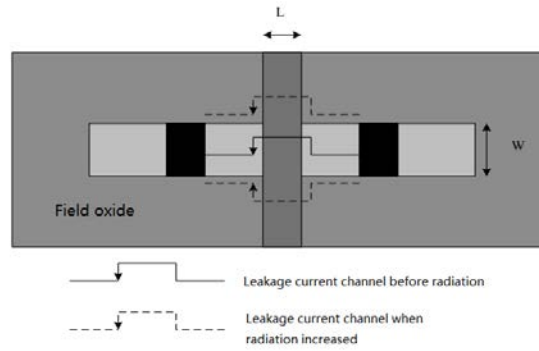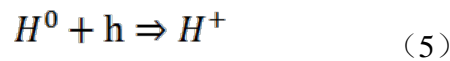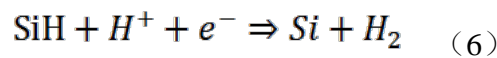oxide, so the substrate inverses which led parasitical leakage tunnel emerge.

Figure3 Irradiation produce leakage tunnel

3.3 *Interface state charge*

Another kind of irradiation defect is interface trap, like the interface trap, which can exchange charges with Si near the interface. Interface state has a significantly impact on carrier's surface mobility and recombination rate. The main composition of interface state is silicon dangling bonds which are similar to the production of oxide layer fixed charges. However, other reactions are taken to form silicon dangling bonds. The very first step of them is between holes and defect containing hydrogen, releasing protons, like H+ in following chemical reaction equation:

$$H^0 + \text{h} \Rightarrow H^+$$

（5）

In positive bias condition, H+ drifts to interface, and following reaction happens in order to form interface state.

$$\text{SiH} + H^+ + e^- \Rightarrow Si + H_2$$

（6）

According to statistics in experiences, the majority of interface trap formed because of protons, but not holes. The velocity of gate to capture and release carriers is related to the bias of gate, so increasing interface state will cause sub-threshold swing to increase in CMOS.

According to the abovementioned study on oxide layer and interface state trap charges, both of the effect of traps to NMOS devices became the center of research. Because border traps and interface state can exchange charges, further study relies on charge pump to measure ac signal to distinct them. Based on the data, the exchange frequency is less than 100Hz; In the center of P_b, the exchange frequency is generally more than 10 times of the frequency in E' center.

4   TOTAL DOSE EFFECT ON NMOS DEVICES

Total dose effect is one of the kinds of ionization irradiation effects. Medium layer such as gate oxide and oxide field in integrated circuit is sensitive area. Irradiation promotes parasitical transistors formation, key parameters degradation and chip consumption.

4.1 *Threshold voltage drifting*

Threshold voltage V_{th} is an important parameter in MOS devices which is between the gate and substrate. Charges in oxide fixed charges and interface state can both change threshold voltage. The changing amount of threshold voltage caused by interface state emergence is based on the following equation.

$$\Delta V_{it} = -\frac{t_{ox}}{\varepsilon_0 \varepsilon_{ox}} q \Delta N_{it}$$

（7）

Considered oxide fixed charges, total dose effect on threshold voltage is based on the following equation.

$$\Delta V_{th} = \Delta V_{ot} + \Delta V_{it} = \frac{t_{ox}}{\varepsilon_0 \varepsilon_{ox}} q(\Delta N_{it} - \Delta N_{ot})$$

（8）

As to NMOS, gate is on positive bias when it is working normally. At this time, fixed charge is far more than interface state charges, so threshold voltage generally drifts negatively and that is the reason why leakage current increases. Along with dose augmenting, negative drifting slows down and the amount of drifting decreases.

The increasing amount of fixed charges relatively becomes less than that of interface state when dose increases. At last, interface effect will become more significant than fixed charges. That is how threshold voltage rebound phenomenon emerges.

4.2 *Trans-conductance degradation*

Trans-conductance g_m shows the ability of controlling currents in MOS devices. The larger trans-conductance is the less gate voltage changes to have a larger change in current intensity, which means a lot to cut down current consumption. When other condition is constant, mobility determines the trans-conductance. Interface traps are formed to whittle down the mobility during radiation and carriers are captured and released to change interface charged. Both of them cause trans-conductance degradation. g_{mr} represents the influence from radiation, g_{m0} represents the original trans-conductance and g_m represents trans-conductance after radiation.

$$g_m = \frac{1}{\frac{1}{g_{m0}} + \frac{1}{g_{mr}}}$$

（9）

5 CONCLUSION

This passage mainly discusses radiation environment, total dose effect principle and influences on NMOS devices to illustrate the effect which total dose effect produces. According to them, this passage further studies how total dose effect impacts working components, providing theory supports to maintain components' normal working in radiation environment.

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