36. AN OVERVIEW ON RADIATION INDUCED DAMAGE

36.1 Review/Background:

So far we have discussed various reliability issues, such as, NBTI, HCI, Dielectric Breakdown, in which various combinations of voltages are applied and the bond dissociation due to the applied voltage is analyzed. However, even if there is no voltage applied, the IC might degrade over time due to radiation. For example, whenever we take a flight, the flash drives that we carry has a high probability of bit-flip. This is entirely due to radiation induced damages (RIDs). RID can cause a plethora of other damages, as well. Let's take a look at the RIDs Some well-known impacts of RIDs are as follows:

- In 1800s, people found electrometers discharged due to ‘unknown’ reasons (radiation induced leakage).
- During atom bomb tests during World War II in the Pacific, Navy reported irreversible failure of electronic components after the nuclear blast [1].
- In 1962, Telestar the first AT&T satellite failed only after 8 months of operation due to Starfish nuclear test in exo-atmosphere.
- In 1978, Intel failed to deliver products to IBM due to radiation related errors.
- 1987: IBM datacenter was hit by radiation-related failures creating industry-wide panic.

Apart from these, radiation damages DNA strings is presumed related to mutation and evolution. However radiation is also constructively used in photosynthesis, disinfecting of medical equipment, food processing and X-ray imaging.

36.2 Radiation Damage vs Electrical Damage:

The damage induced by radiation is totally different from electrical damage. Electrical damages lead to defects at the Si-SiO₂ interface or within the bulk of SiO₂. However radiation induces defects in the body of crystalline silicon. This didn’t happen in the defects considered in the previous lectures. The magnitude of the impact is humongous. Depending on their energy, a proton that impacts releases around 4000
electron hole pairs, a neutron 40000 and an alpha particle millions. Radiation can also create damages unforeseen in previous lectures, e.g., gate rupture by hole punch through.

In Figure. 36.1 it is shown how radiation induces damage into a MOSFET device. Let’s assume gate and drain voltages are not big enough and does not cause any significant damage. If a charged particle comes along, i.e., proton, alpha particle, (we will talk about neutron later), it will excite all the electrons around it (Coulombs law). As a result many of the electrons sitting in the valance band will be ejected (like solar cell) and they will generate a lot of electron hole pairs. Every one of them can be 100fC. This in turn will perturb the electrostatic temporarily (Yellow box in middle figure). It would not be that important if this phenomenon happens in the bulk due to high doping in the bulk. However, if this happens in the junction, it would have tremendous effect and the PN junction would temporarily lose its properties. The MOSFET would malfunction and therefore the whole logic surrounding the transistor would be affected. This can be a big issue if it happens frequently.

The second issue is if the particle hits the SiO\(_2\) (green layer on top) then you could have a punch-trough in dielectric without applying a voltage. This would cause a permanent damage (hard error). We will study this later in these series of lectures about radiation.

![Figure. 36.1. Mechanism of radiation induced damage in a MOSFET.](image)

One way to solve is to cut off the region where the charges being generated. For example, while in silicon it the charge generation, due to is short band gap (1ev) and smaller energy required(3.1ev), is relatively easy, in SiO2 this is not the case (band gap is 9.2ev and energy required is between 20 to 30ev). Therefore, as you can see in the right figure the region where charge being generated is much smaller for SOI and therefore the performance would be better.

In the rest of this lecture as well as next lectures we will discuss how big this yellow box
could be, how many particles will be generated, and what type of reactions happens that generate those particles, and at the end of the day I will tell how people coping with this.

Figure. 36.2 shows how simulations can help to estimate radiation sensitivity. This is simulation of a MOSFET. A certain drain bias is applied and field lines can be observed. A particle has coming through a corner. As it can be seen in the left figure after 25fs everything seems normal and nothing much is happening (particle is going through the device). Around 10ps, a perturbation on potential toward right corner of the figure can be observed. At about 100ps this effect is maximum, and at this point transistor might malfunction and does not work properly. However, after a micro second when the track is gone, then transistor is back to normal. So, if transistor somehow survives this initial millisecond or microsecond pulse then it will continue to operate under its normal condition. One should note that as the devices are getting smaller and smaller the amount of perturbation would be larger, because the same amount of particles are being generated in a smaller volume.

Figure. 36.2. Simulation helps to estimate radiation sensitivity

36.3 Radiation Damage in Various Types of Components:

Depending on the class of ICs, different ICs have different impacts. Some classes of ICs (such as nonvolatile memory) are historically sensitive to total-dose
radiation. Even within a class of IC, total dose hardness can vary widely between/within manufacturer. In Figure. 36.3 TID (Total Ionizing Dose) Failure Threshold is plotted against different class of ICs. As it can be seen SRAMs are the most susceptible while Nonvolatile memories are least affected.

![TID Failure Threshold vs IC Class]

**Figure. 36.3.** TID hardness varies widely among different class of ICs.

The impact of radiation damage can be broadly categorized into two categories: soft reversible error and hard irreversible error. Losing a bit in flash memory (changing it from 1 to 0 or vice versa) due to radiation is an example of soft error. As it can be seen in Figure. 36.4, a flash memory includes a Floating Gate (FG - Low Bandgap Material), which has an oxide and a Control Gate (CG) deposited on top of it. By applying a large bias through CG, the electrons tunnel from the channel to FG and therefore the trap charges are created in FG. This in turn changes the threshold voltage, and thus the drain current will be lower. This way you write one. The reverse process produces zero. You read basically by looking at the channel current associated with this two state. Now, if you have a radiation such as the one shown in Figure. 36.4c, then the stored charges will interact with coming charges and the resulted electrons would spill over the gate and ones becomes zero. The impact of radiation is equivalent to emptying a cup full of charge. The number of charges in the floating gate region is much less than that would be generated by even a neutron strike. Thus there is an error in the data stored by the memory unit. This error is called a soft error in Flash memory, because it can be recovered.
But now let's see why this error is important. Figure 36.5 shows number of electrons as a function of gate length. When the gate length is on the order of a 40nm or so, then you have only 100 electrons stored. So if you have a charge loss associated with this, when radiation particles came and there is a spill over, if we have 5% charge loss, or 10% charge loss, you can have significant shift in a VT. Because 5% charge loss is on the order of less say 10 or 5 so this is a significant fraction of the original charge loss and you may not be able to tolerate it. So how do you design in this presence of radiation is a big concern.

Figure 36.4. Structure of a Flash memory: (a) Erased Cell, (b) Programmed Cell, (c) Disturbed

Figure 36.5. Number of electrons versus floating gate (FG) length in a Flash memory.
In flash memories, the floating gate holds not more than 500 electrons. So for reliable operation we cannot allow loss of more than 1 electron/year. However radiation stress creates hole punch through thus leading to steady leakage (Figure. 36.6 a). A register like structure, within the oxide, is drown. That's the percolation path. Unlike TDDB, the set of red boxes will form instantaneously as the particle is going through, and if that happens then there will be a permanent short circuit. So all the charges stored in the floating gate will essentially drain. And this time you cannot make it any better. This is something called a permanent damage, Irreversible hard damage in a flash memory.

Figure. 36.6. (a) Hole punch in flash memories (b) Radiation accelerates degradation. The plot shows that the degradation is higher for higher LET (Linear Energy Transfer)

Figure. 36.7. Radiation induced hard breakdown characteristics.
In Figure. 36.6 b, experiments to estimate and project breakdown are shown. In the experiments before the radiation you have some distribution of $V_T$. This is because the oxide thickness might be slightly different. Now we need to accelerate the radiation, get the estimated damage and then project back to the operating condition. Using heavy particles which one can damage equivalent to one hundred protons is a way of accelerating radiation. So these chlorine, bromine, nickel and iodine, are like accelerators, to get the estimated damage and then projecting it back to the operating conditions.

It is important to note that hole punch through created by radiation leads to characteristics (Figure. 36.7) which are akin to soft breakdown (SBD) seen in TDDB (Figure. 36.7) [2, 3].

In Figure. 36.8, some nomenclatures and terminologies of radiation are presented and attributed to soft and hard errors. Soft error is when you can restore things back to the previous condition (before the damage), and hard error occurs when you cannot restore the damage.

![Nomenclature Diagram](image)

**Figure. 36.8.** Various other terminologies used in radiation study.

### 36.4 Sources of Radiation and Other Definitions:

There are three sources of radiation damage, namely, Cosmic rays, ceramic package can have radioactive contaminants that can cause damage, and thermal neutron that interacts with Boron($B_{10}$). If the thermal neutron comes in and strikes a $B_{10}$ then it produces a cascade and that can cause an upset. Shielding is ineffective against high-energy
atmospheric neutrons, and can’t be used for on-chip sources of alpha-particles. The aforementioned sources are shown in Figure 36.9. Three primary mechanisms of radiation, alpha particles, low and high energy neutrons, are summarized in Figure 36.10. Due to these mechanisms, there are the following types of radiation error:

![Diagram](image)

**Figure. 36.9.** Sources of radiation damage in a transistor.

![Diagram](image)

**Figure. 36.10.** The radiation mechanisms [4,5,6].
1. **Total Ionization dose (TID) – Quasi permanent:** Cumulative long term ionization damage that results in trapped holes at Si/SiO2 interface in gate & field oxides

2. **Displacement damage (NIEL) – Permanent Damage:** Cumulative long term non-ionization damage that results in the creation of defects in the semiconductor materials (increases SILC in oxides and recombination current in bulk)

3. **Transient or single event effects (SEE) – Soft error:** Caused by a single charged particle as it passes through a semiconductor material e.g. heavy ions and protons. Requires reset.

### 36.5 Important definitions

Since the topic of radiation damage is being introduced in this lecture, it is important to be familiar with certain terms and their definitions. These would be extensively in the next few lectures.

1. **Dose (D) or Absorbed radiation dose**: energy deposited (ergs or Joules)

2. **Total ionization dose (TID) or Absorbed radiation dose rate** \(=\frac{dD}{dm}\) = energy deposited/mass of the material (J/kg=\(m^2/s^2\)). Units 1 gray (SI)=1J/kg , 1 rad (CGS)=100 ergs/gm=10mGy (erg=mJ)

3. **Stopping power**: energy absorbed/length of matter (MeV/cm)

4. **Linear energy transfer (LET)**: charge generated by stopping power.

\[
ET[fC/\mu m] = 10^{15} \times \frac{q \times LET[MeV/\mu m]}{\Delta E}
\]

36.1

\(\Delta E\) is 3.6 eV in Silicon and 20 eV in SiO2.

5. **Equivalent LET** = LET(MeV/cm)/target density (mg/cm\(^3\))=97 MeV-cm\(^2\)/mg for silicon=1 pC/mm

Note that equivalent LET is 100 times more than LET. Also Equivalent LET is roughly independent of material.

### 36.6 Nuclear Reaction to Charge Neutral Neutrons

As it is discussed, since \(\alpha\)-particle is charged, it will generate a significant amount of charges as it is coming down. On the other hand this is not the case for neutrons as they are not charged. So the question is if neutron will go through without interaction? The answer is neutron will go through without reaction until it finds another nucleus, then it
will have a nuclear reaction. This reaction will produce $\alpha$-particles, and these $\alpha$-particles in turn will then interact with the device. Hence, neutron will not interact directly. It will talk to the device through nuclear reaction, through fragmenting a nucleus. Only then it can cause damage. But now the question is how thick the material should be in order for a nuclear reaction? Here we are going to do a simple calculation to find this out.

Consider a silicon slab. It might be approximated that in a single plane the entire surface encounters at least one nucleus in its path (Black Wall, Figure. 36.11b). Now the area of one nucleus is

$$\sigma = \pi r^2 = \pi[(28)^{\frac{1}{3}}r]^2 = 5 \times 10^{-25} \text{cm}^2$$  \hspace{1cm} 36.2$$

where 28 accounts for the number of nucleons in the silicon nucleus (14 protons, 14 neutrons), $r$ is the radius of one nucleon (~1.3e-13cm). With certainty there will be at least one strike, since this is a wall.

Now the atom density in the black wall can be found as

$$\text{Black Wall} = \frac{1}{\text{area/atom}} = 2 \times 10^{24}\text{atom/cm}^2$$  \hspace{1cm} 36.3$$

This density however is when seen from a plane, along the depth atom density leads to an interaction depth of

$$\text{Interaction depth} = \frac{\text{Black Wall}}{\frac{\text{atoms}}{\text{cm}^3}} = \frac{2 \times 10^{24}}{5 \times 10^{22}} = 40\text{cm}$$  \hspace{1cm} 36.4$$
where \(5 \times 10^{22}\) is the number of atoms/cm\(^3\). Using equation 36.4, we can find the probability of a hit as \(10\mu m/40\text{cm}=1/40000\). So, one in 40000 neutrons will cause nuclear reaction. Now, the integrated number of neutrons in 10 years \(\sim 10^6\). Hence the total number of hits \(10^6/40000=25\text{hits/cm}^2\). The typical active area of an IC=0.04cm\(^2\). Thus the number of hits per IC =25\times0.04=1. This means, if you combine all the transistors in one place without interconnects then the number of hits within a IC in a given time is guaranteed to be equal to 1. So you will have at least one nuclear reaction within ten years in your IC and there is no way to avoid it. Therefore, one must design an IC that when this happens the IC would continue to work and is not dead.

### 36.7 Generation of Carriers

Once you have a hit, either with alpha particle or neutron that is heating a Si\(_{28}\), (see Figure 36.10), then this will create fragments, and these fragments will generate electron hole pair. Similar to a solar cell. Once the electron hole pairs are generated then the potential will be perturbed and subsequently the transistor will not function.

![Figure 36.12. A radiation impact creates localized electron-hole pairs](image-url)
Electron hole pairs created by radiation are localized, unlike the e-h generated by light shining on a semiconductor which is uniform. The localized e-h pair generated is shown in Figure. 36.12.

Most of the time, there will be a transient charges build up. That is shown in red and blue in Figure. 36.12. The electron hole pairs will be generated, but there will be a little electrostatic influence. This is because the numbers of electrons generated will be equal to numbers of hole generated. In that case, if the mobility (electrons and holes) are exactly the same, then there will be no problem in terms of electrostatics. If you have the same numbers for electrons and holes generated, there will be no change in the total electrostatics. And of course there will be no damage. Of course the electron and hole mobility are not the same. There would be some differences and that would cause the upset.

People do different types of simulation ranging from Classical Drift-diffusion simulation, Monte-Carlo approaches, Stochastic circuit simulation, and then eventually try to calculate how many upsets you have in a given IC for a given amount of time.

36.8 Conclusion

Radiation induced damage has been a reliability concern for semiconductor devices and this susceptibility to radiation has made military application of ICs very different than commercial ones. Radiation errors continue to be an important concern today – particularly for various types of memories. Understanding radiation error requires an appreciation for the physics of radiation sources, the nuclear reaction within the material, and the sensitivity of a device in response to electron-hole pair generation. Just like other semiconductor transport theories, various hydrodynamic and Monte Carlo models are used for predictions.

36.9 References

[1] www.spectrum.org March 2997, p. 36-37 explains how satellite communication was disrupted by tests of the atom bomb.


36.10 **Review Questions:**

1. **Why is SOI more radiation hard compared to bulk devices? What do you feel about radiation hardness of FINFET?**

   The active volume in SOI is small, therefore the number of electron hole pair generated within that volume is smaller and therefore it is more radiation hard. FINFET has thin body and therefore it has the same behavior as SOI with regard to radiation and it would be radiation hard.

2. **What type of radiation issues could arise for thin-body devices like FINFET?**

   Answered in question 1.

3. **What is error correction code (ECC)? Why does it correct for MBU?**

   ECC is a system of adding redundant data, or *parity data*, to a message, such that it can be recovered by a receiver even when a number of errors (up to the capability of the code being used) were introduced, either during the process of transmission, or on storage. Since the receiver does not have to ask the sender for retransmission of the data, a back-channel is not required in forward error correction, and it is therefore suitable for simplex communication such as broadcasting. Error-correcting codes are frequently used in lower-layer communication, as well as for reliable storage in media such as CDs, DVDs, hard disks, and RAM.

   MBU stands for Multiple Bit Upsets and as it is explained can be corrected by ECC.

4. **What is the difference between SEE and SEU?**
5. What is ‘displacement damage’? What is its unit?

6. What is LET? What are the two types of units used to describe LET?

Linear Energy Transfer. [MeV/µm] and [fC/µm].

7. Explain the origin of the term Blackwall? What is the blackwall thickness.

It is deep 40 cm in Si. It is like looking at the bottom of a 40 cm deep hole which looks dark. Now you bring that dark surface to the top (bringing all the atoms at the bottom to the top)