Space Weather Effects on Microelectronics Devices around the LEO Spacecraft Environments

W Suparta

Space Science Centre (ANGKASA), Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia.

E-mail: wayan@ukm.edu.my

Abstract. Orbiting spacecraft will always be affected by the space environment through their interactions. The main trigger depends on the variability of the radiation environment around the spacecraft such as galactic cosmic rays, solar particle events and the trapped particles. In the low-Earth orbit (LEO), the trapped particles in the radiation belts play a crucial role in affecting the spacecraft in any orbit. The common effects of radiation on spacecraft are charging where some spacecraft components accumulate electric charge from their environment which in turn damaged the spacecraft systems. In addition, space weather will create a stream of charged particles that are associated with solar flares and coronal mass ejections. In this paper, we study the effects of solar radiation on a low orbiting spacecraft (LEO) that would be applied to the equatorial region. Radiation effects in microelectronic components are also discussed. These effects in the radiation environment on an LEO spacecraft are very important in design and testing to mitigate and protect the system from serious damages.

1. Introduction

The failure of Malaysian RazakSat-1 in orbit gives us a stern warning that we need to accommodate the impact of the trapped particles near the spacecraft in the development of a Low-Earth Orbit (LEO)-Equatorial. RazakSat-1 is the second remote sensing near equatorial orbit (NEqO) satellite launched on 14 July 2009 after TiungSat-1. The satellite was designed to operate with a low inclination orbit (9 degrees) at altitude of 685 km, which intended to provide greatly increased coverage of Malaysia with a mission lifetime of 3 years. Unfortunately, they were confronted with an anomaly and terminated in their orbit on 30 August 2010. The cause of the failure is still a mystery. However, we expect that the equatorial orbit makes it trapped in the particle radiation hazards of the South Atlantic Anomaly (SAA). SAA is a part of the inner radiation belt that due to the offset of Earth' magnetic poles and geographic poles lead close to the Earth's atmosphere. SAA is centered in Brazil sky lies from -90° to +40° of longitude and from 0° to -50° of latitude. SAAs are mainly contained of charged particles in several levels of energy up to 10^2 keV for electrons and 10^2 MeV for protons. These particles can harm spacecraft that passed through, especially for LEO orbit [1, 2].

The development of LEO-Equatorial orbit satellite is very important for Equatorial countries, which will increase daily coverage the region than the polar satellite. The challenge is faces more radiation hazard impact rather than the polar satellite because it more frequent passes SAA, and consequently, the exposure time of the trapped particle radiation is longer than the polar satellite. Some sophisticated space weather hazard information system, such as SPENVIS [3] has been developed to simulate space environment hazard. Horne et al. [4] studied the forecasting of high-energy trapped particle in the outer radiation belt area using SPACECAST. Particularly in the inner of radiation trapped particle, models based on physics-magneto hydrodynamic (e.g., [5]) and statistical (e.g. [6]) framework has been employed. We have employed the spatio-temporal hierarchical Bayesian (STHB) model to preliminary forecast the daily trapped particle over the SAA region [7] by applying a Kriging interpolation technique to make the contour distribution map of particle flux in the geographic coordinate [8] and the result was compared with NOAA map.

The purpose of this paper is attempted to study the impact of space radiation hazard in an LEO-Equatorial orbit environment. Due to advantages development of spacecraft in these environments, the radiation damage, total dose and radiation flux, and kind of device loaded should be clearly quantified. As in [9], the major radiation damage can be come from (a) *cosmic rays* in all directions, which majority consisting of protons; (b) *solar particle events* come from the sun direction which consist of a large flux of high-energy (several GeV) protons and heavy ions; and (c) *Van Allen radiation belts* contain electrons (up to ~10 MeV) and protons (up to 100 MeV) trapped in the geomagnetic field. The position of the damage source above poses a concern for satellites, especially a spacecraft that employs complex modern electronics. Studying the effects of radiation environment on LEO spacecraft is very important to mitigate and to protect of our spacecraft from serious damages.

2. Variability of Solar Activity

Figure 1 gives an overview of the solar data for 23rd solar cycle with period of 12 years and 6 months. The variability of solar activity is represented by the sunspot number (SSN), radio solar flux ($F_{10.7}$), solar wind and solar energetic particles (galactic cosmic rays - GCRs). Data for SSN and $F_{10.7}$ on daily basis collected from NOAA - Space Weather Prediction Center (SWPC) website are covered from May 1996 to November 2008, is presented in the first panel. The solar wind proton in the second panel (ACE/SWEPAM) consisting of density (**B**), temperature (**C**) and its speed (**D**) is presented due to it a stream of charged particles released from the Sun. In Figures 1E-F show the GCRs from ACE/CRIS with seven level energies for Carbon (C), Nitrogen (N) and Oxygen (O) elements, and the last panel shows the flux of solar energetic particles (SEPs) from ACE/SIS with a similar element as Figures 1B-D, but we choose for energy level (MeV/nuc) of C_54.3-76.3, N_59.2-83.3 and O_63.8-89. The solar wind, cosmic rays and SEP data from 1 September 1997 to 30 November 2008 are collected from the Advanced Composition Explorer (ACE) satellites (http://www.srl.caltech.edu/ACE/). All the data collected on daily basis is processed into a 27-day average to monitor the trend during one solar cycle.
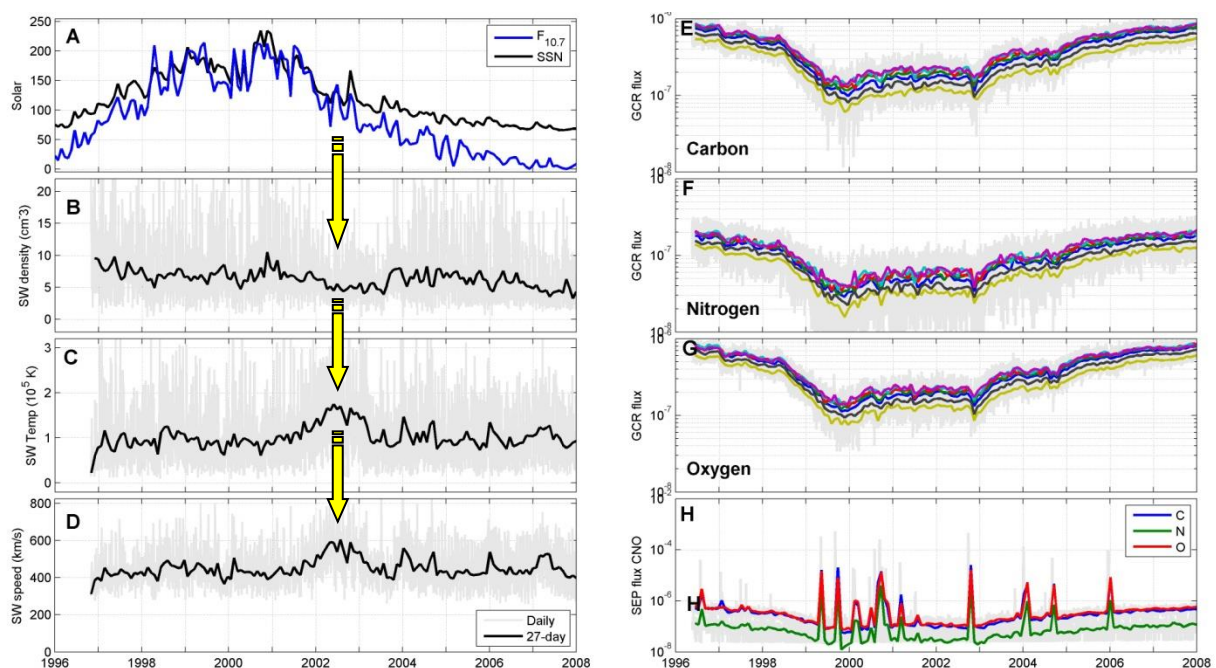

Figure 1. The variability of solar energetic particles during the 23rd solar cycle from May 1996 to November 2008. A down arrow in the left of figure shows the geomagnetic storm on October 2003. The grey background shows the daily average and otherwise is a 27-day average.

As shown in Figure 1, the solar flux maximum was occurred around November 2001. However, one interesting event as indicated by down arrows is Superstorm October 2003. During this event, SSN reached more than 200 and the high-speed stream in the solar wind corresponds to the temperature and density, which indicate that how deep it will penetrate into the Earth's atmosphere. This impacted density of solar wind at the 27-day average, which opposite to that of temperature. In the right panel of Figure 1 clarified that the galactic cosmic rays was opposite to that of SSN/$F_{10.7}$. Although some noises recorded in Figure 1H, the trend of SEP was similar to that of GCR, which both for N are observed 25% lower than C and O. In general, the variability of solar energetic particles that generated space radiation is very crucial to the object in space (e.g., spacecraft). This radiation triggered by GCRs originated from the intergalactic medium, solar particle events (SPEs) which consisted of high fluxes of charged particles, primarily protons associated with solar flares (SFs) and coronal mass ejections (CMEs). One effect of this radiation on spacecraft is charging. Therefore, a specific previous of solar storm in October/November 2003 is presented once to document what has been missed to monitor space weather effects on a spacecraft.

3.   Space Weather Phenomena Impact on Spacecrafts

One of the space weather phenomena is a geomagnetic storm. These phenomena can softly or harder damage electronics onboard spacecraft. An example case of space weather associated with geomagnetic storm variation during the Superstorm 2003 (known as the Halloween storm) is presented in Figure 2. The data on hourly basis are from 22 October to 7 November 2003, which covers the period of Superstorm from 29 to 31 October of the year. From top to bottom the panels, the solar activity is characterized by the South (B_z) component of interplanetary magnetic field (IMF B_z), the solar winds (velocity, density and temperature for protons) and SEPs (Ion, Proton and Electron).
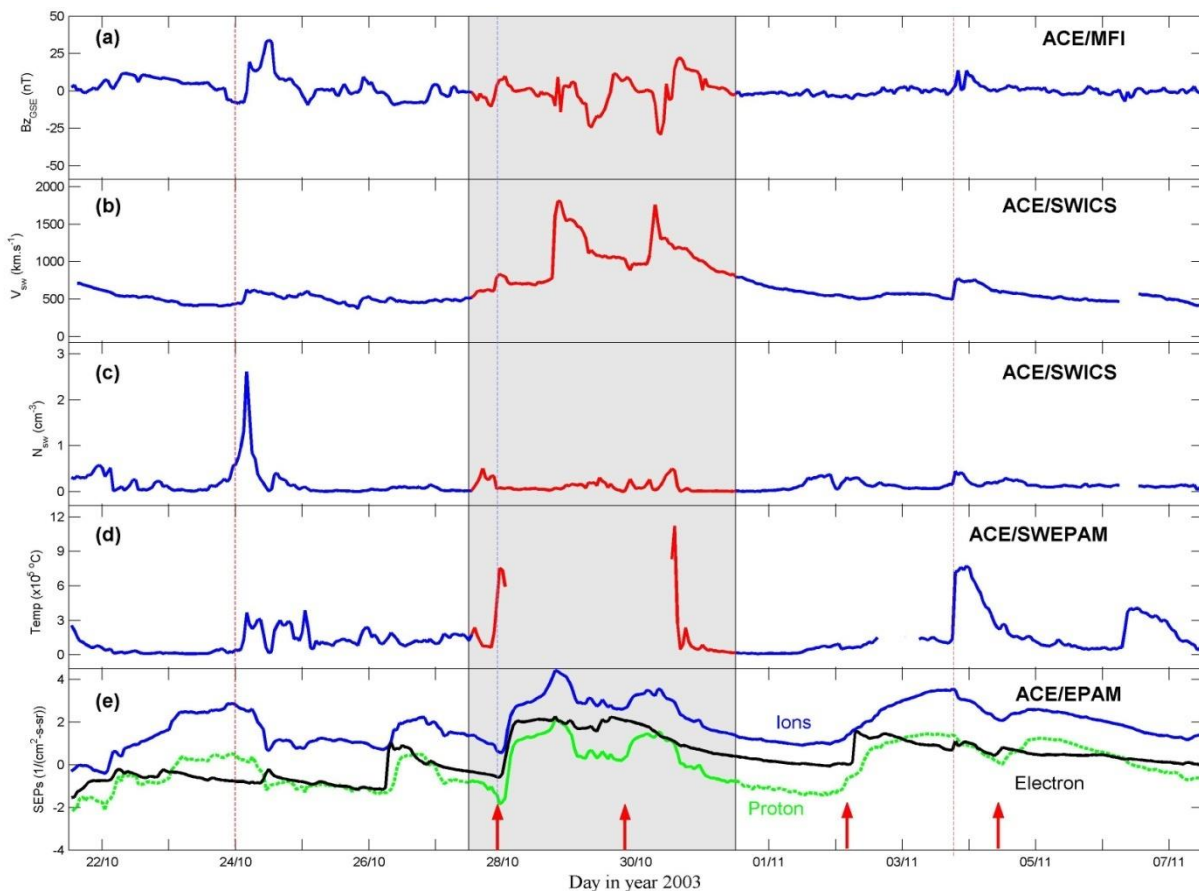

Figure 2. Variability of IMF Bz, solar wind and SEPs during a geomagnetic storm of October 2003.

As shown in the figure, the grey background highlighted are the beginning and ending of the occurrence of the Superstorm. The storm has two distinct episodes, preceded by a high solar activity on solar wind speed (see Figure 2b). The first storm episode peaked by a shock at ~06:00 UT on 29 October with solar wind speed > 1,850 km/s followed by the first shock of IMF B_z minima at ~01:00 UT with value ~-25 nT. The second storm episode was occurred at ~18:00 UT on 30 October with a speed > 1,710 km/s, followed by second IMF B_z minima at ~23:00 UT with value ~-30 nT. During this event, the solar wind density was recorded a low with small ripples and solar wind temperature was missing due to the tremendous of event. However, solar energetic particles were increased together, as indicated by an up arrow in the figure. A complete of explanation of geomagnetic storm on October/November 20013 of this work can be found in Suparta et al. [10] and Suparta [11]. In general, the high plasma densities and temperatures are associated with the interaction of the fast solar wind plasma and magnetic fields (ICMEs) with the slower upstream plasma [12]. More specifically on solar-energetic particles that included in, is presented in Figure 3.
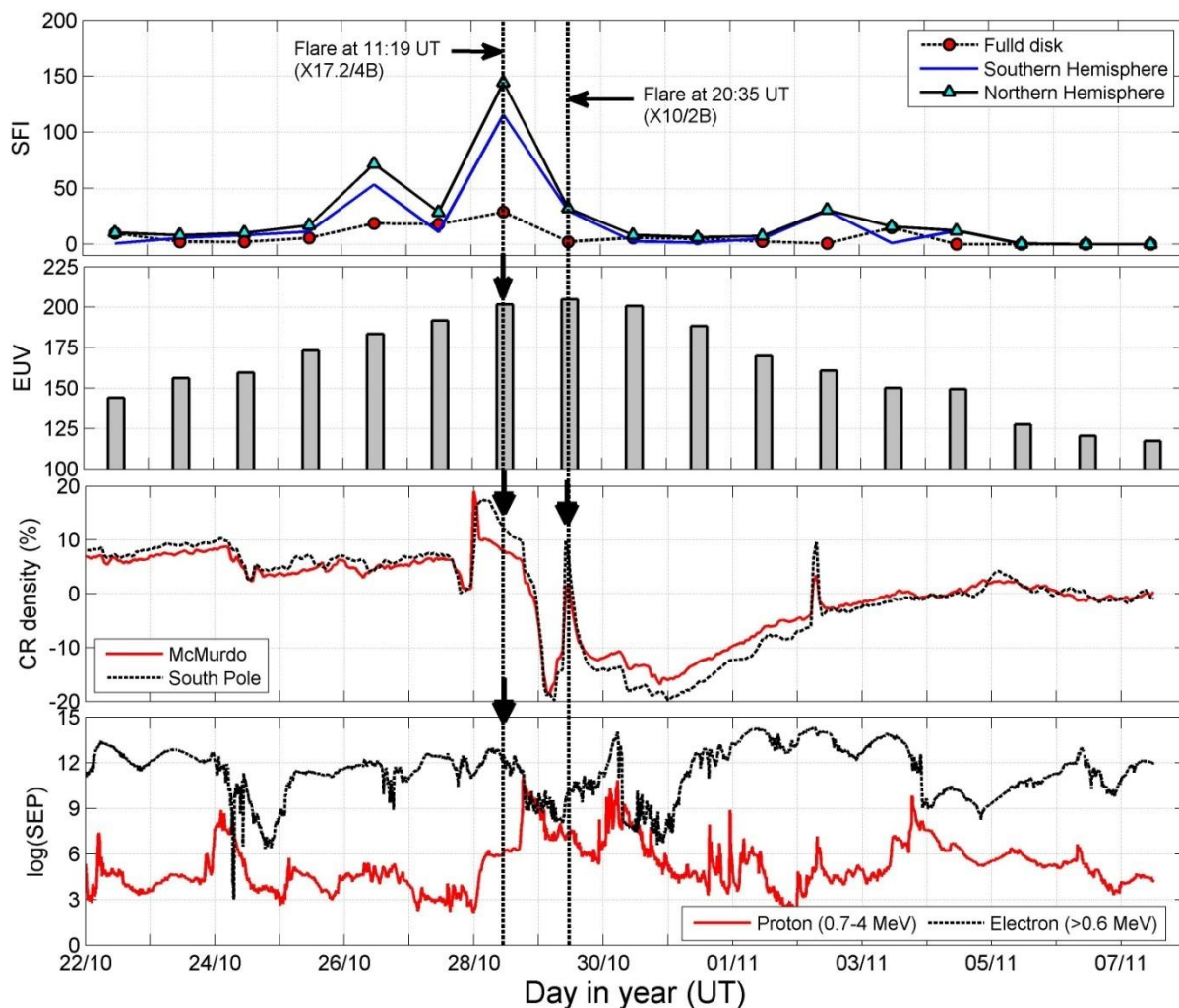

Figure 3. Solar energetic activity and PWV variation observed from 22 October to 7 November of 2003. The vertical dashed line shows the time occurrence of flare activity (X17.2/4B and X10/2B), which shows the shock time wave of both flares, and down arrows shows the association between solar activity and the upper atmosphere parameters. The original figure was reproduced from the paper of Suparta [11].

Since solar particles have unimpeded access to a spacecraft outside the magnetosphere, we present the variation of solar flare index (SFI), extreme ultraviolet (EUV), solar cosmic ray density (SCR) and solar energetic particle variations during the period of events. The peak of SFI for Southern Hemisphere region was measured maximum on 28 October 2003 associated with X17.2/4B flare. Solar full disk is a summation of Southern Hemisphere and Northern Hemisphere regions. The solar EUV (λ = 10-120 nm) radiation affecting the upper ionosphere and is higher during the intense of solar flares. The percentage of cosmic ray (CR) density from ground-based neutron monitors at McMurdo and South Pole stations in Antarctica showed a jump abruptly and the higher fluxes of CR nuclei was modulated by a strong shock wave (SW). The last panel of Figure 3 shows the natural logarithmic of SEP for electrons and protons (obtained from NOAA/GOES), which showed a significant enhancement of proton fluxes in both energy intervals associated with SW. In general, the sudden increase of proton peak is coincided with sudden storm commencement and X28 flare activity. This impulse when interact with Earth's magnetic field produce changes in the near-Earth space environment. In addition, solar flares increased the radiation levels in the atmosphere due to the increase in trapped particles in the Van Allen belts. Finally, the particle radiation coming from space, degrade the capability of spacecraft systems, such as microelectronics systems which will be presented in the summary and discussion section.

4. Summary and Discussion

As a brief presented in Section 2 and Section 3, we can see that the sun emits energy that drives changes in the interplanetary environment. The changes in the vicinity of the Earth's magnetosphere modulated by the sun during active and inactive phases of a solar cycle are accelerated by solar flares (SFs) and coronal mass ejections (CMEs). This solar particle event which consists of both protons and heavier ions with different composition will affect inclination and altitude of the orbits. In addition to the solar wind plasma, interplanetary space contains high-energy charged particle called GCRs. During a solar blasting event, solar energetic particles produce significant variation in the CR density. Specifically, spacecrafts are exposed from low to high latitudes, which including particle radiation, ultraviolet irradiation, neutral particles and space debris. Interaction of high-energy ionizing radiation with semiconductor materials can cause degradation, interference or malfunctions of spacecraft systems. Therefore, radiation damage to microelectronic circuits and devices will particularly address in this section. The basic mechanism of how the space radiation environment creates charged tracks in semiconductor electronics is briefly presented.

An important effect occurred from interaction of semiconductor material and high-energy ionizing radiation is so-called the single event effect (SEE). SEE's are caused by high-energy protons and cosmic rays (heavy ion). Heavy ions in the form of electron-hole pairs cause a circuit failure due to plasma track is collected in the sensitive circuit node. The collected at a junction or *p-n* contact is greater than the charge carrying in the threshold component. The most SEE errors are occurred in the SAA region due to protons are trapped in the Van Allen belts. Below are several types of SEE's and they can be classified into soft or hard errors [9, 13]. Soft errors are nondestructive to the device and normally interrupt the normal operations or halt. Hard errors may be physically destructive to the device with permanent functional effects.

- **Single-event upset (SEU)** is a change of state or transient induced by an ionizing particle such as a cosmic ray or proton in a device. This may occur in digital, analog, and optical components or may have effects in surrounding circuit. Penetration of electrons with energies greater than 10 keV can accumulate charge inside the spacecraft resulting various effects such as SEU.
- **Single-event latch up (SEL)** is a potentially destructive condition involving parasitic circuit elements to a single event. In traditional SEL, the device current may exceed device maximum specification and destroy the device if not current limited.
- **Single-event burnout (SEB)** is highly localized burnout of the drain-source in power MOSFETs. SEB is a destructive condition.

- **Single Event Transient (SET)** – an error in term of a reset or rewriting of the device causes normal device behavior thereafter.
- **Single Hard Error (SHE)** - an SEU which causes a permanent change to the operation of a device. An example is a stuck bit in a memory device.
- **Single Event Gate Rupture (SEGR)** - a single ion induced condition in power MOSFETs which may result in the formation of a conducting path in the gate oxide.
- **Multiple Bit Upset (MBU)** - an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system.

Figure 4 shows an example of how high-energy of solar radiation threats the microelectronics devices in a CMOS memory cell. In Figure 4a, ionization effects caused charged particles and lattice will be affected due to ones of the ion energy is too low [9]. The ionization effects are usually transient, creating glitches and soft errors. They change the arrangement of the atoms in the crystal lattice, increasing the number of recombination centers, depleting the minority carriers and affected semiconductor *p-n* junctions. One illustration of the SEU soft error in the common 6 transistor SRAM cell is presented in Figure 4b. In that configuration, T_2 and T_4 are PMOS, and T_1 and T_3 are NMOS, where T_5 and T_6 are the access point for reading and writing cell. When the external charged come in (e.g., GCR), the memory cell will in state '1', T_3 and T_2 will be conducted (ON), and T_1 and T_4 will OFF. Consequently, potential at points Q and $\bar{Q}$ are equals V_{cc} and 0 (ground), respectively. If the ion beat deposit with enough charge into the channel beneath the gate oxide (poly-Si), the T_1 will temporaly switch ON and the potential at point Q would suddenly reduce and become close to zero. If T_1 is ON long enough, consequently, low voltage occurs at the gate of T_3 and turns it into OFF. This implies that soft effects will occur in T_1, and then T_2 and T_4 will change their state leading to eventually a bit flip.

As a conclusion, the mitigation of these soft errors in modern microelectronics due to space radiation has become important, not only space electronics but also in general commercial electronics. The radiation hazard during geomagnetic storms or substorms is also important to be taken into account in estimating accurately the impact of space weather because of hot plasma will be injected from the magnetotail into the nightside high-altitude equatorial regions that will affect the LEO-Equatorial inclination.
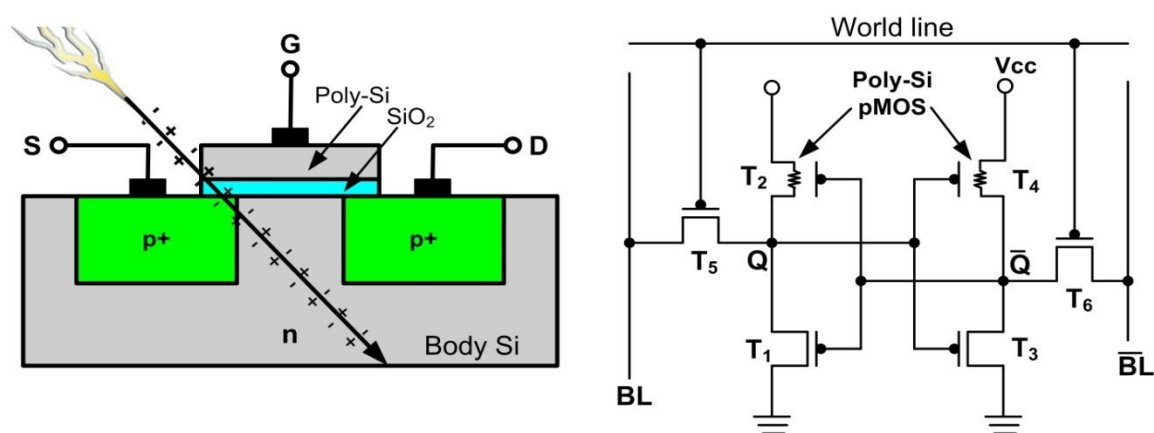

Figure 4. (a) Schematic view of a particle hit in a pMOS transistor and (b) a basic configuration of a 6-transistor SRAM cell

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