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Programme: M.Sc., Medical Physics

Course Title : Electronics and Instrumentation
Course Code : MP104

Unit-III
Ionizing Radiation Effects in Electronic Devices and Circuits

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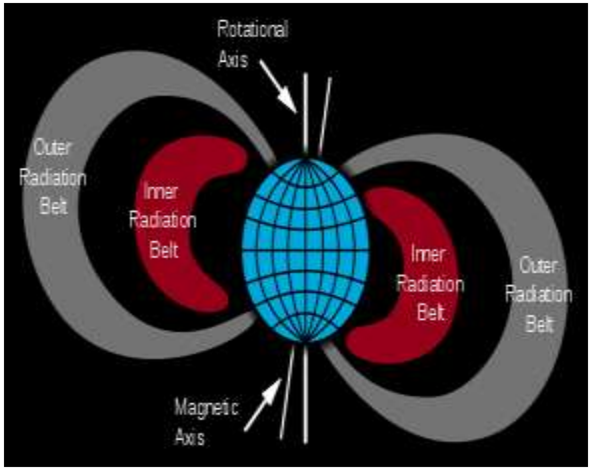
Radiation environments:

From a historical standpoint, the study of radiation effects in electronic circuits started in the early 60's mainly as a response to two concerns:



- **The increasing demand for hardened electronics that could survive the impact of a nuclear explosion (nuclear arms race was in full swing at the time)**

- **The discovery of radiation belts by Van Allen and Vernov and the resulting need for protection from them (in the wake of early space exploration)**

- **The first steps of electronics can be dated back to about the same period:**

The first satellite (Sputnik 1, 1957) appeared at the same time as the first integrated circuit in germanium (1958); the metal-oxide semiconductor (MOS) transistor was born in 1960, just the same year as the first interplanetary space probe Pioneer; the Apollo program was a contemporary of the first 256-bit computer memory

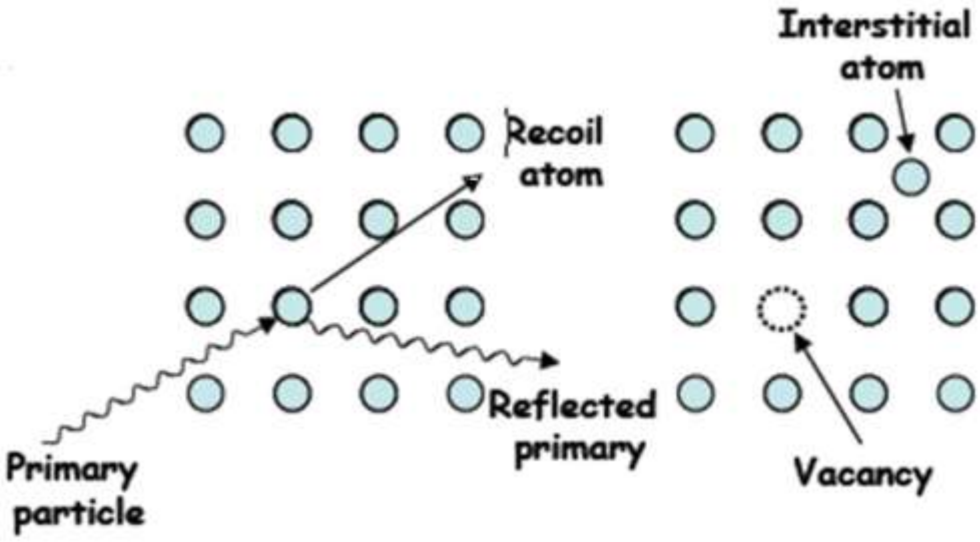
Radiation effects in electronic devices: Effects of radiation may change depending on the particular operating principle of the considered electronic device.

Basic damage mechanisms in semiconductor devices:

❑ Despite the complexity of the interaction processes and their dependence on the properties of the incident particle and of the target material, two are the basic radiation damage mechanisms affecting semiconductor devices

➢ Ionization damage: takes place when energy deposited in a semiconductor or in insulating layers (SiO2), frees charge carriers (electron-hole pairs), which diffuse or drift to other locations where they may get trapped, leading to unintended concentrations of charge and parasitic fields; this kind of damage is the primary effect of exposure to X- and γ-rays and charged particles; it affects mainly devices based on surface conduction (e.g. MOSFETs)

Displacement damage (DD): incident radiation dislodges atoms from their lattice site, the resulting defects altering the electronic properties of the crystal; this is the primary mechanism of device degradation for high energy neutron irradiation, although a certain amount of atomic displacement may be determined by charged particles (including Compton secondary electrons); DD mainly affects devices based on bulk conduction. (e.g. BJTs, diodes, JFETs)



Displacement effect in a bidimensional crystal

Basic effects of radiation damage:

Effects of radiation in semiconductor devices can be included in one of two broad classes

Total dose (TD) effects: are due to the progressive build-up of trapped charge in insulating layers or at the Si/SiO2 interface (as a consequence of ionization phenomena) or of defects in the bulk of the devices (originating from accumulation of displacement events)

Single event effects (SEE): are due to charge deposition induced by a single particle that crosses a sensitive device region; the effects may lead to destructive or non-destructive damage of the device

❑ SEEs occur stochastically, while TD is cumulative and may become visible after the device has been exposed to radiation for some time

❑ TD is usually related to long term response of devices, whereas SEE is concerned with short time response

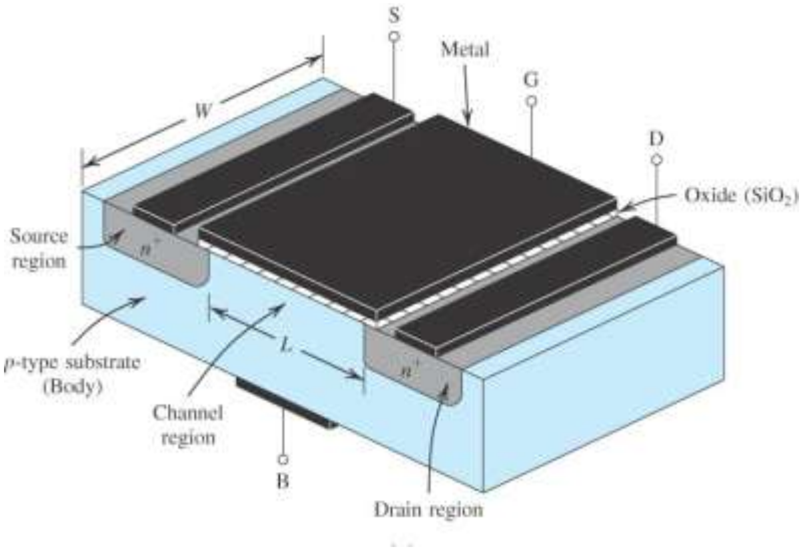
❑ Only a tiny part of the device is affected by SEE, corresponding to the position of the particle strike, while TD uniformly affects the whole device, because it results from the effect of several particles randomly hitting the device

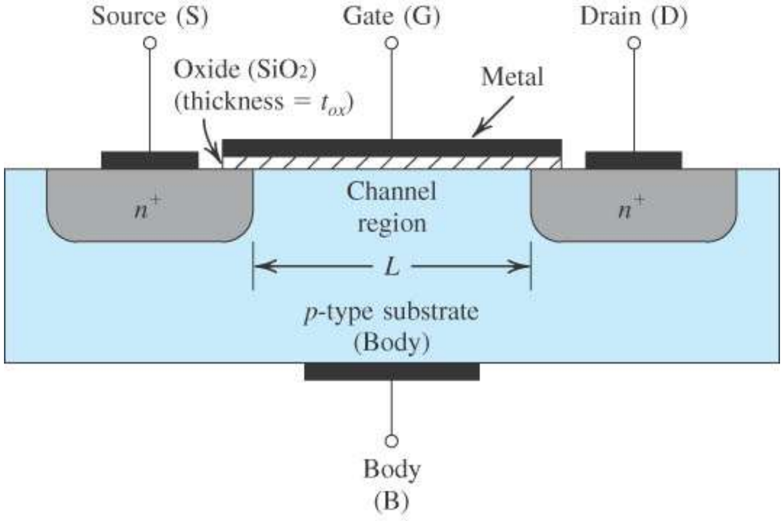
❑ As far as SEE is concerned, the most important figure is the rate of occurrence; TD is characterized by the maximum drift of the main device parameters

Radiation effects in MOSFETs: Metal oxide semiconductor field-effect transistor (MOSFET) technology has become dominant in the fabrication of integrated circuits (in particular digital) because it enables the design of very high density, low power systems

❑ **MOSFET transistors come in two flavors, N-type (using electrons as carriers) and P-type (where the current flowing in the device channel is made of holes)**

❑ **Fabrication of MOSFET transistors requires a sequence of processing steps, performed on a silicon wafer (generally less than 1 mm thick and 30 cm in diameter) including ion implantation, thermal cycling for diffusion and damage annealing, deposition of oxides, metal strips and masking layers and selective attack of the wafer surface (etching)**





Operation of the MOSFET transistor:

In an enhancement mode NMOS device

- Heavily doped N-type source and drain regions, at the two ends of the device channel, are fabricated in a P-type substrate (often called the body)
- A thin layer of silicon dioxide is grown over the substrate material and a conductive gate material (metal or polycrystalline silicon) covers the oxide between source and drain; during device operation, the gate-to-source voltage is used to control the current flowing between source and drain; this control can be used to provide gain in analog circuits and switching characteristics in the case of digital circuits
- In general, the minimum value of the channel length L which can be achieved in a given technology is used to provide a measure of the lithographic limitations of the fabrication process
- **If a positive voltage is applied to the gate terminal, at first free holes will be repelled from the region of the substrate under the gate, leaving behind a depleted region populated with bound negative charges (ionized acceptor atoms)**
- **If the gate voltage is further increased, electrons from the n+ source and drain regions are attracted into the channel region; when a sufficient number of electrons has accumulated near the surface of the substrate under the gate, an N region is created, connecting the source and drain regions**
- **If a voltage is applied between the drain and source, a current flows through this induced N region (also called inversion layer), carried by mobile electrons**

the value of VGS at which a sufficient number of mobile electrons accumulates to form a conducting channel is called threshold voltage and is usually denoted V_t

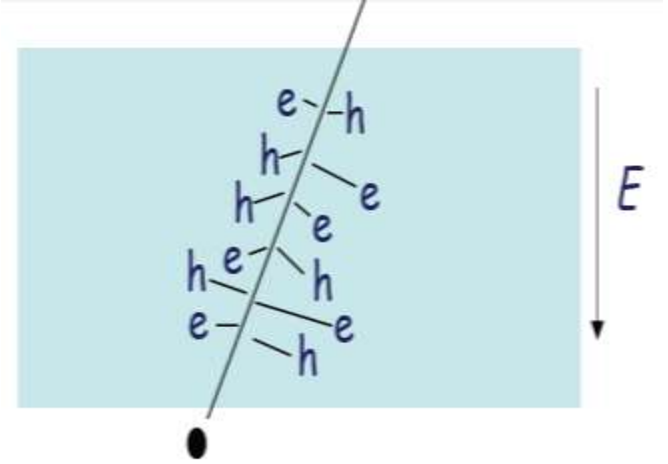
Total ionizing dose effects in MOSFET structures:

- ☐ An MOS device exposed to an ionizing radiation environment typically suffers degradation in one or more of its parameters (threshold voltage, gate voltage to drain current gain, or transconductance, channel leakage, noise); changes may not be constant with time after irradiation and may depend on the dose rate
- ☐ An integrated MOSFET circuit may slow down, show higher leakage (parasitic) currents, or even cease functioning properly (catastrophic failure)
- ☐ Damage responsible for these total dose effects occurs in the insulating layers (SiO2) of the device structures and at the interface between the silicon substrate of the device and the oxide, and consists of three components:

- ➢ Buildup of (positive) charge trapped in the oxide (the gate oxide and/or the field oxide, used to isolate devices from each other)
- ➢ Increase in the number of interface traps
- ➢ Increase in the number of traps in the oxide bulk

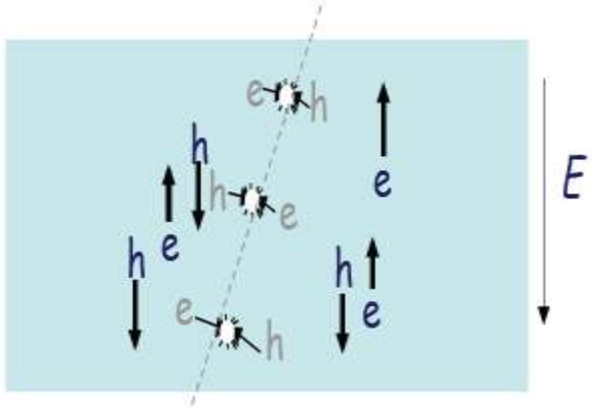
Carrier generation and transport in the oxide:

❑ When a particle passes through the MOS structure, it ionizes the lattice atoms, leaving behind free electron-hole pairs along its track



❑ In the gate oxide, part of the pairs recombines; the remaining electrons and holes are separated by the applied electric field

- ➢ Electrons move towards the gate; electrons are very mobile in SiO2 and quickly get out of it through the gate contact
- ➢ Holes move towards the Si/SiO2 interface; holes have a very low effective mobility and transfer via a complicated, stochastic trap-hopping mechanism



❑ Since the number of e-h pairs is proportional to the deposited energy, the total damage is also roughly proportional to the total absorbed dose

Carrier transport in the oxide

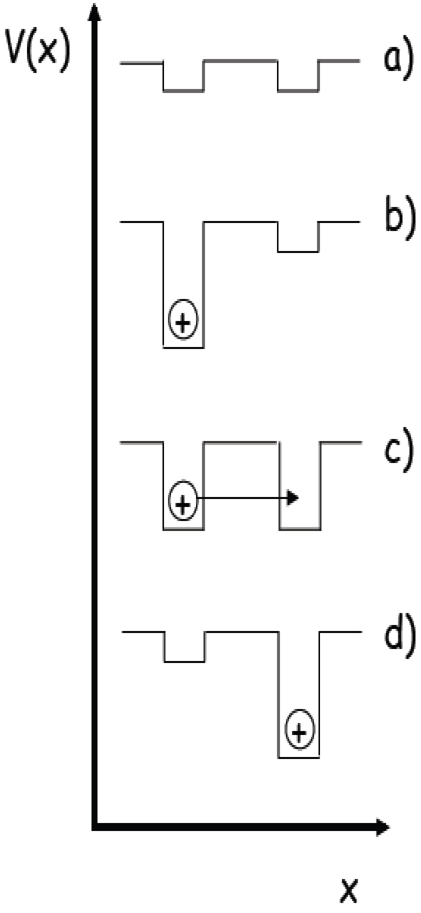
- **Some of the holes may be trapped within the oxide, leading to a net positive charge (the ratio between trapped holes and trapped electrons is somewhere between 103 and 106); others may move to the Si/SiO2 interface, where they can create an interface trap by capturing electrons.**

- **Along with the electron-hole generation and/or hole transport processes, chemical bonds in the oxide structure may be broken; in particular, bonds associated with hydrogen and hydroxyl groups may release hydrogen ions (protons), which may migrate to the Si/SiO2 interface and undergo a reaction resulting in the creation of interface traps; also defects created in the oxide bulk can migrate and form interface traps.**

- **Generally, interface traps can trap both holes and electrons by capturing them from the device channel; their state depends on the bias conditions and type of the device**

Hole transport mechanism (polaron hopping)

Let us start with an initially empty localized trap a); when a hole, while moving through the oxide, gets stuck in it, the total energy of the system is lowered by a distortion of the lattice around the trap site b); the hole digs a potential well itself, i.e. is self trapped



The transition of the trap between two nearby sites occurs via an intermediate thermally activated state c), which thermal fluctuations of the system momentarily br the electronic energy levels very close to each other; the hole tunnels from the first to the second site

In the final state of the process, the hole resides in the second site d), the transition probability depending on the tunneling transition probability and on the probability that the intermediate state in c) is created

Electronic noise

- **The word “noise” is used to indicate spontaneous fluctuations of electric variables taking place in passive and active electronic devices.**

- **Electronic noise originates from the fundamental physical phenomena which underlay the operation of electronic components (e.g., thermal agitation of charge carriers, granularity of electric charge); such phenomena cannot be eliminated without denying fundamental physical laws.**

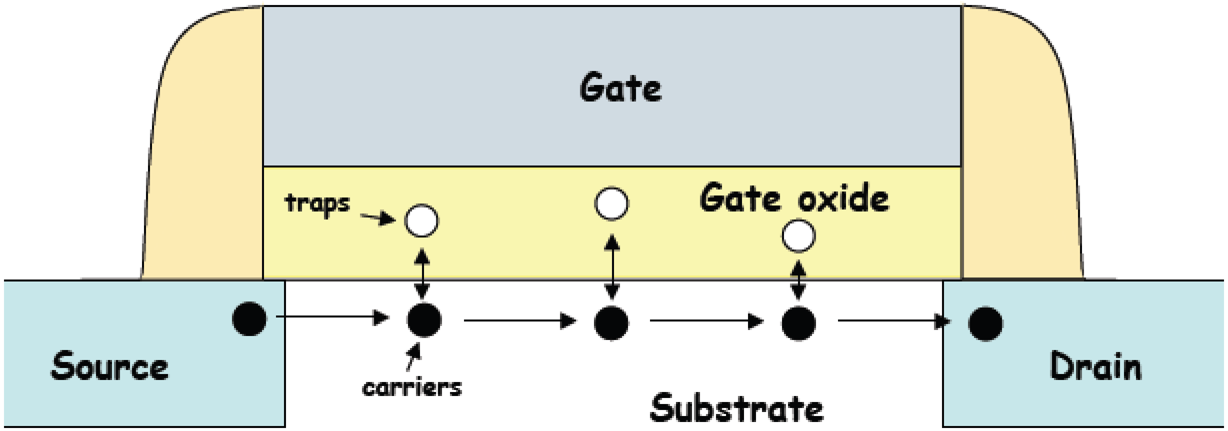
- **Noise has a different nature from that of other disturbances coming from the environment (e.g., 50/60 Hz harmonics from the power supply, electromagnetic induction from other circuits), which, at least theoretically, can be suppressed by shielding or filtering techniques.**

- **Noise may impair the capability of a circuit to accurately measure the amplitude of a signal and represents the unavoidable, final limitation to the performance of an electronic system**

- **Since noise is a random process, its properties can be described only through statistical tools and quantities (e.g. mean square value, root mean square, or rms, value, power spectral density)**

1/f noise in MOSFETs

- In MOSFET devices, 1/f noise is due to the interaction between carriers in the channel and traps in the gate oxide; the process of random capture and emission of carriers is responsible for a fluctuation in the number and mobility of carriers, resulting in a stochastic fluctuation of the drain current.
- Experimental investigations show that 1/f noise is almost entirely due to the so called border traps, traps in the oxide located within 3 nm of the Si/SiO2 interface, which can exchange charge with the underlying channel with characteristic times of the same order of an electrical measurement.
- Border traps exchange charge with the channel with a probability exponentially decreasing with the trap distance from the Si/SiO2 interface.
- **The definition of a trap as a border trap depends also on the operating conditions (in particular on the gate to- source voltage, VGS).**



Noise increase in irradiated MOSFETs

- ✓ Exposure to ionizing radiation also affects the noise performance in MOSFET devices.

- ✓ As far as white noise is concerned, the gate referred power spectral density (the noise voltage spectrum is the square root of the power spectral density) increases due to the radiation induced reduction of the channel transconductance g_m.

- ✓ **Flicker noise increase is correlated with the increase in positive trapped charge close to the interface and with the increase in the number of border traps.**

Evolution of radiation effects in MOSFET

Radiation-induced threshold voltage shift has been gradually eliminated by the natural evolution of advanced microelectronic technologies, where the gate oxide thickness has been reduced generation after generation.

Now the main radiation hardness issues in microelectronic circuits are those relevant to the isolating structures (radiation induced leakage currents, positive charge build-up in the field oxide, in particular the shallow trench isolations), affecting both static and noise properties of MOSFET devices, together with single event effects.

Gate oxides with dielectric constant larger than in SiO_2 (High-K oxides) will be used to reduce the gate leakage current and alleviate some reliability issues; on the other hand, such new dielectric materials still need to be appropriately tested from the standpoint of radiation-tolerance

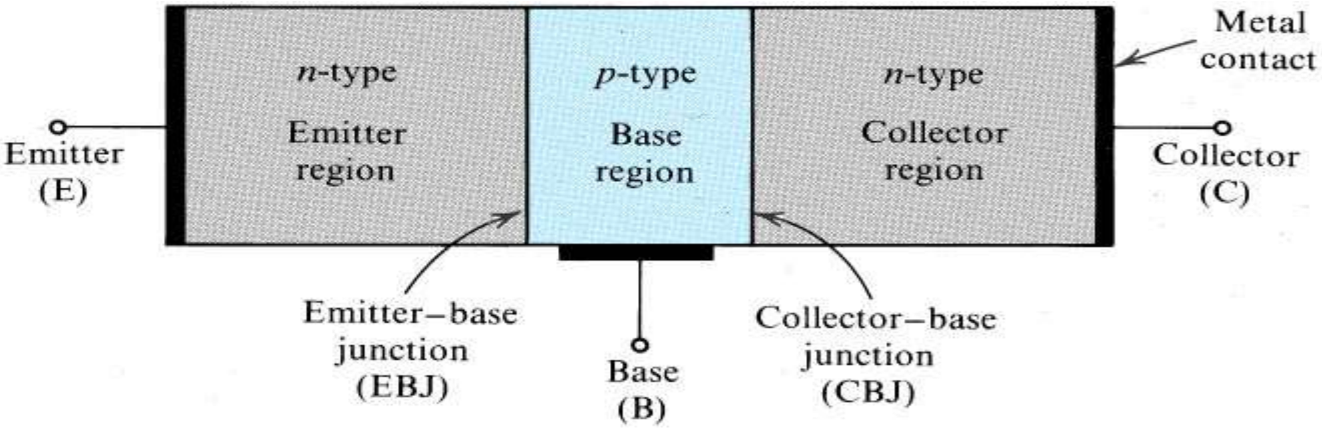
Radiation effects in BJTs

Bipolar junction transistors (BJTs) are widely used for analog applications where they may still offer some advantages with respect to MOSFET devices

❑ The bipolar transistor consists of two PN junctions connected in series (back to back in an NPN transistor); the term bipolar indicates that in the device, the current is conducted by both electrons and holes

❑ A BJT consists of three semiconductor regions, with alternating doping type, called the emitter, the base and the collector; therefore the BJT comes in two flavors, NPN (see the figure) and PNP; the three regions form the emitter-base and the collector-base junctions

❑ As an amplifier, the BJT is operated in the direct active region, i.e. with VBE>0 (BE junction forward-biased) and VBC<0 (BC junction reverse-biased) in an NPN device



Operation of the BJT:

❑ Let us consider an NPN transistor operated in the direct active region

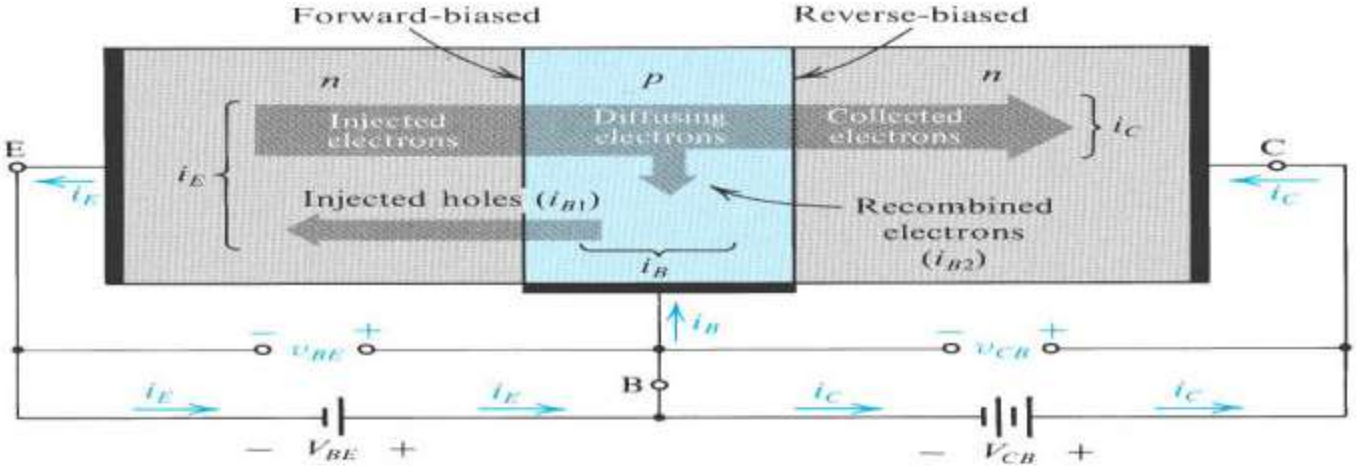
❖ the forward bias on the EB junction will cause a current, the emitter current **I_E, to flow across the** junction; the current will include holes injected from the base into the emitter and electrons from the emitter into the base (the latter providing the dominant contribution)

❖ the electrons injected from the emitter into the base will be minority carriers in the P-type base region; they diffuse through the base region towards the collector and are swept across the CB junction depletion region

❖ some of the electrons that diffuse through the base region recombine with holes, which are the majority carriers in the base and are provided by the base terminal through the **I_B** current; since the base is usually quite thin, the fraction of electrons lost through this recombination process is small; then, the collector current

$I_C=I_E-I_B$

❖ the common-emitter current gain, **$\beta=I_C/I_B$, provides a measure of the** electron recombination in the base



Total dose effects in bipolar transistors

- ❑ Operation of BJTs is based on the diffusion of minority carriers, e.g., electrons in the P-doped, thin base region; since BJT operation does not depend on surface potentials, as in MOS structures, bipolar transistors are less sensitive to ionizing radiation than MOSFETs
- ❑ Gain degradation and, to a lesser extent, leakage increase at the base-collector junction, are the most striking and common effects of radiation in bipolar transistors
- ❑ Two are the main causes for gain degradation
- ❖ displacement in the bulk: bulk damage is responsible for an increase of the recombination centers, therefore reducing minority carrier lifetime
- ❖ ionization of the passivation oxide layers (particularly of the oxide covering the emitter-base junction): by a process similar to the one taking place in MOS devices, charge trapping and generation of new interface states are responsible for the gain degradation
- ❑ Since the probability of recombination of minority carriers in the base depends on the transition time, bipolar transistors with shorter bases are more radiationtolerant

Gain degradation due to bulk damage

- Mid-gap states in the silicon band-gap facilitate the recombination of minority carriers in the base of a bipolar transistor, therefore reducing its current gain
- Atomic displacement induced by irradiation is responsible for an increase in the concentration of the recombination centers and for a reduction of the minority carrier lifetime
- Damage is strongly dependent on the radiation type and energy and on the silicon doping concentration

Gain degradation due to ionization damage

- The electric field due to hole trapping in SiO2 passivation over the base-emitter junction may widen the space charge region at the base surface, causing an increase in the IB component due to recombination current in the BE depletion region
- With the same process as the one described for MOSFET, interaction of holes with oxide lattice defects containing hydrogen atoms may also be responsible for trap build up at the Si/SiO2 boundary, thus increasing surface recombination velocity in the base region
- Hole trapping in the oxide and trap build-up at the silicon/oxide interface both contribute to gain degradation; such a contribution is represented by the relevant gain damage
- Degradation due to ionizing radiation is more significant at small collector currents; this is in agreement with the fact that radiation induced excess current in the device base comes from recombination phenomena in the space charge region, which predominates at small base-to-emitter voltages

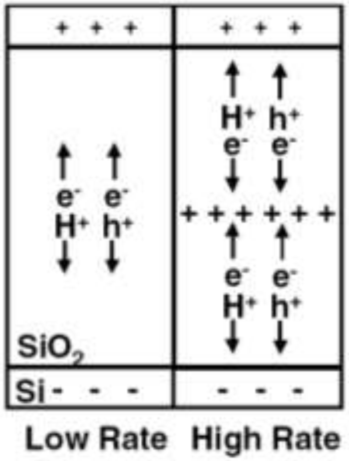
Dose rate effects in BJTs

❑ Bipolar transistors are known to suffer from the so-called enhanced low dose rate sensitivity (ELDRS); dose rate used in ionizing radiation testing have a profound effect on the amount of surface degradation suffered by the device; this implies that accelerated radiation testing, normally done at dose rates thousands of times higher than those experienced in real applications, could have a strong impact on the test results

❑ While in irradiation facilities, to reduce testing time, typical dose rates lie generally between 10 Gy(SiO2)/s and a few mGy(SiO2)/s, they, for instance, amount to less than 10-4 Gy(SiO2)/s in space applications and to about 5x10-4 Gy(SiO2)/s in high energy physics experiments

❑ Suppression of radiation sensitivity of thick oxides at high dose rates can be considered a space-charge limited effect; positive oxide-trapped charge provides a deterrent particularly for interface trap formation; this type of positive charge appear to be able to escape the oxide if given time or extra vibratory energy by heating; therefore, if a given dose is administered rapidly at 100°C, the result is similar to that dose being given slowly at room temperature

❑ At high dose rates, radiation-triggered migration of H+ ions from oxide defects to the Si/SiO2 interface, and the consequent trap formation, is prevented by the electrostatic barrier raised by the oxide trapped charge; the opposite may happen under low dose rate conditions; low dose rates are more effective in PNP transistors, where the only ionizing damage mechanism at work is the one involving trap formation at the Si/SiO2 interface (the very mechanism which is enhanced by low dose ra



Radiation hardening techniques

❖ In some cases, mainstream market forces, which drive the evolution of microelectronic technologies, may indirectly improve the radiation resistance of electronic devices (e.g., device speed in bipolar transistors, device scaling in complementary MOSFETs).

❖ Whenever a device is not sufficiently radiation hard for the foreseen application, some measures can be taken to make it harder; this can be obtained by:

✓ modifying the device geometrical layout (**hardening by layout**)

✓ modifying one or more steps of the fabrication process (**hardening by process)**

✓ suitably designing the overall circuit or system (**hardening by design)**

❑ **Commercial technologies for integrated circuits commonly evolve by improving on speed, scale of integration, complexity and power dissipation; many of the technology developments needed to achieve these results have been beneficial in terms of radiation-tolerance.**

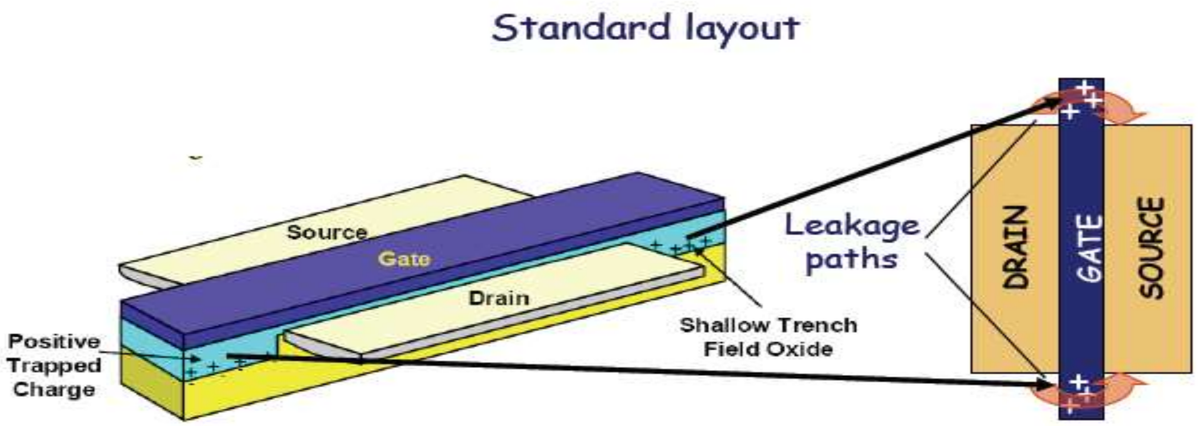
❑ **Commercial deep submicron CMOS technologies can already provide total ionizing dose hardness levels in the range of several units up to several tens of megarad; use of ultra-thin (a few nm) oxides limits the effects of oxide trapped charge; use of thin epitaxial layers, retrograde wells and shallow trench isolation improve hardness against latch-up.**

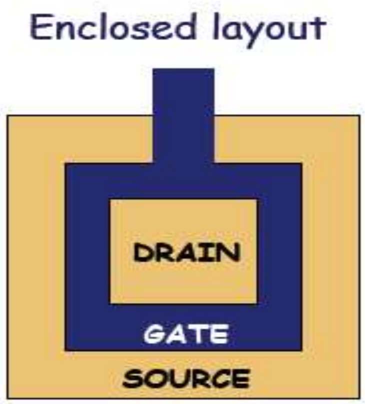
Radiation hardening techniques

- **SOI technology is of significant commercial interest because of the advantages it offers in terms of speed, power and integration density; the fact that it also offers total device isolation is an advantage in terms of radiation effects; because of the insulating layer, the technology is immune to destructive latch-up.**

Hardening by layout

- In irradiated NMOS devices, positive charge trapped in the shallow trench isolation oxides is responsible for the formation of conductive paths along the STI sidewalls
- If an enclosed layout is used, no parasitic path can form between source and drain, because there is no thick oxide layer running along the main channel





Hardening by process and by design

- A large number of steps are involved in the fabrication of a typical MOS integrated circuit and many of these steps can influence the radiation hardness of a device; the most important factors are those which affect the charge trapping characteristics of the oxides (gate oxide, field oxide, intermetal oxide) and the relevant interfaces
- Deep submicron technologies are generally more sensitive to single event upset than older technologies; however, tolerance to SEU, can be improved by means of design techniques; in the case of digital circuits, a typical solution involves using logic redundancy, which may consist, for instance, in the triplication of the digital processing chain integrated in a majority voting system (in this case, a radiationinduced error in one bit may be outvoted by the other two, not affected components)

Dosimetry

❑ Measurement of the amount of energy absorbed by (or of the particle or photon flux striking) a sample exposed to a radiation source.

❑ Dosimetry methods have been developed to deal with the two different effects radiation may have on crystals.

✓ deposition of **ionization energy in silicon dioxide, silicon and a few other materials** involved in the fabrication of electronic circuits

✓ **non-ionizing energy loss (NIEL), mainly in the form of atomic displacement in** crystalline lattices.

❑ Deposited energy is measured in rad (corresponding to the specific energy of 100 erg/g) or Gray (Gy, an SI unit, corresponding to the specific energy of 1 J/kg); based on the definitions, 1 Gy=100 rad (remember that 1 erg=10-7 J).

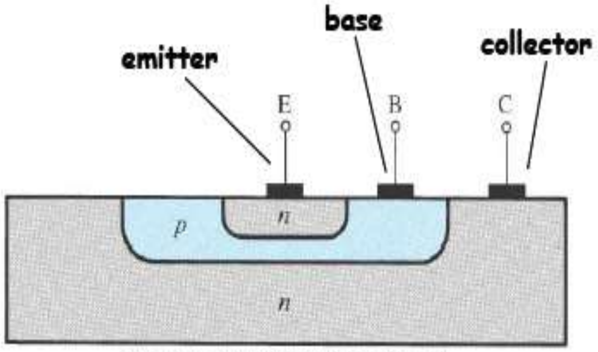
❑ Particle flux is generally measured in (number of particles) cm-2s-1; particle fluence is measured in (number of particles) cm-2 and is, by definition, the time integral of the particle flux.

Basic mechanisms of radiation damage

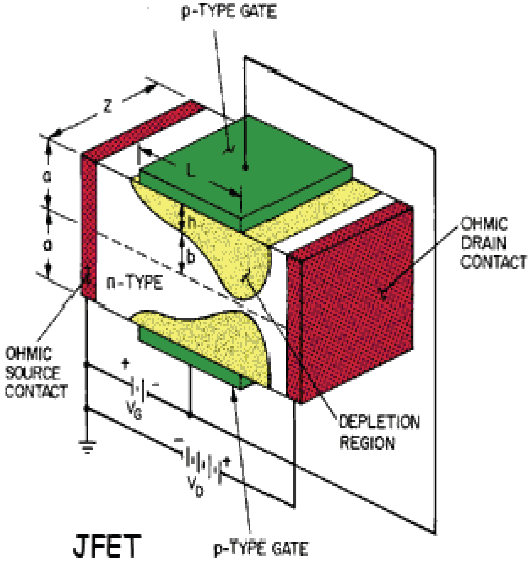
Radiation can interact with matter (and, in particular, with semiconductor material) through different mechanisms, producing different effects on different kinds of devices and circuits.

Effects in bulk-effect devices:

- In bulk-effect devices, the main device current flows in the bulk of the device, generally far enough from any surface between different materials (e.g., Si and SiO2).
- Bulk-effect devices are particularly sensitive to dislocation damage, which is responsible for degradation of average carrier lifetime (due to recombination phenomena), mobility decrease and carrier density reduction.
- **Bipolar junction transistor (BJT) operation is based on minority carrier diffusion and can be strongly affected by average carrier lifetime degradation, leading to degradation in the current gain**
- **Junction field-effect transistor (JFET) operation is based on majoritity carrier dirft and can be strongly affected by carrier trapping phenomena leading to gate leakage current increase and appearance of Lorentzian noise components in the drain current**



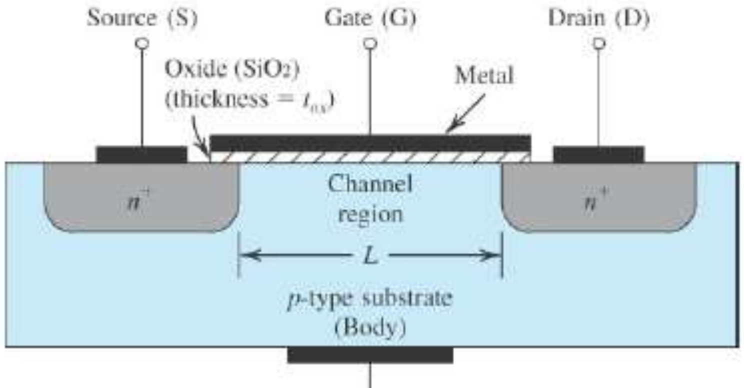
Bipolar junction transistor



JFET

Effects in surface controlled devices

- ❖ In surface-controlled devices, the main device current flows at the interface between two layers of different materials, e.g. silicon and silicon dioxide in MOSFETs.
- ❖ **Surface-controlled devices are particularly sensitive to ionizing dose effects, which are responsible for charge trapping in SiO2 layers and for an increase in Si/SiO2 interface state density.**
- ❖ **Operation of the metal oxide semiconductor field effect transistor (MOSFET) is based on majority carrier drift at the interface between SiO2 and Si (on the silicon side); it can be strongly affected by charge trapping in the gate oxide and by surface effects due to capture and release of carriers from the device channel, which can lead to threshold voltage shift, parasitic leakage currents and mobility degradation.**
- ❖ **MOSFETs are also sensitive to single event effects, which can produce destructive (e.g., circuit burnout) or non-destructive (e.g. bit flip) damage.**



Interaction of radiation with matter

- There are many different sorts of radiation environments where an electronic system may happen to be operated
- In each environment, electronic circuits may be exposed to (a mix of) different kinds of radiation and particles which, from the standpoint of radiation-matter interaction properties, can be grouped in three major categories

1. photons (highly energetic photons, X and γ-rays are of particular interest)
2. charged particles (electrons, protons, α-nuclei and heavy ions)
3. neutrons

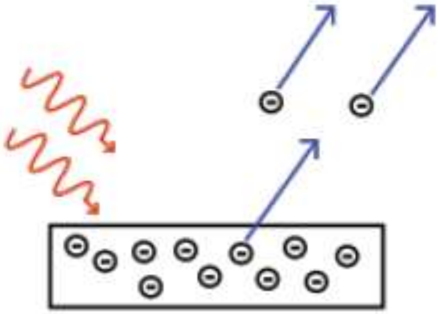
- The interaction of such particles with matter depends on several factors, namely on the mass, charge state and kinetic energy of the incident particle and on the atomic mass A, atomic number Z and density of the target material
- A particle (whether a photon, a charged particle or a neutron) impinging on a semiconductor electronic device may damage it through one of two basic mechanisms

1. ionization
2. displacement

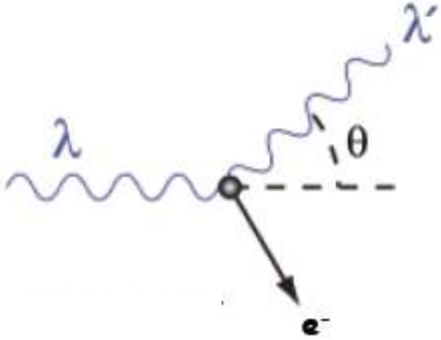
Photon interaction with matter

Photons interact with matter through one of three different mechanisms, according to the atomic number of the target atom and the energy of the incident particle:

1. photoelectric effect
2. Compton scattering
3. pair production

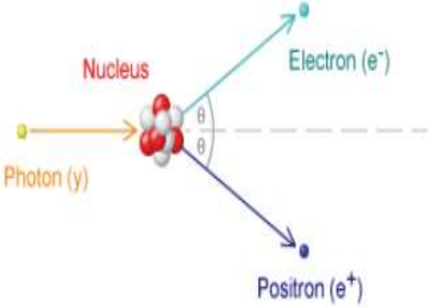


Photoelectric effect: in the photoelectric absorption process, the incident photon, after interacting with an atom of the target material, completely disappears; in its place, an energetic photoelectron is ejected by the atom from one of its bound shells; the photoelectrons appears with an energy $E_{e-}=h\nu-E_b$, where $h\nu$ is the energy of the incident photon and E_b is the binding energy of the electron in its original shell.



Compton scattering: it is the predominant interaction mechanism for γ-ray energies typical of radioisotope sources (like 60Co); for silicon (Z=14) the Compton effect dominates for energies of the incident photon between 50 keV and 10 MeV

Pair production: the process becomes energetically possible when the energy of the incident photon exceeds twice the rest mass of the electron, i.e. 1.02 MeV (the probability is actually very low below 2 MeV); in the interaction the photon disappears and is replaced by an electron-positron pair; all the energy exceeding 1.02 MeV goes into kinetic energy of the newly generated particles



Charged particle and neutron interactions with matter:

- ❑ **Charged particles interact with matter mainly through Coulomb scattering;** the charged particle, upon entering the target material, immediately interacts with many electrons simultaneously; depending on how close the particle gets to atoms, Coulomb forces may be sufficient to either rise an electron to a higher lying shell within the atom (**excitation) or to completely** remove the electron from the atom (**ionization); nuclear interaction,** including elastic scattering and possible atom displacement or transmutation of the target atom can take place when heavy charged particles are involved.
- ❑ **Neutrons interact with matter by collision with atomic nuclei:**
  - ❖ In an **elastic scattering process, the neutron gives up a portion of its energy to an** atom of the target material, eventually dislodging the atom, which is referred to as primary recoil, from its lattice position; the primary recoil can in turn displace other lattice atoms
  - ❖ **Inelastic scattering involves the capture of the incident neutron by the nucleus of the** target atom and subsequent emission from the nucleus at a lower energy; the nucleus, left in an excited state returns to its original condition by emission of a gamma-ray
  - ❖ **Transmutation reaction involves the capture of the incident neutron by the target** nucleus and subsequent emission of another particle (a proton or an α particle); the remaining atom is thereby converted into another element

Semiconductor devices and circuits

- Modern microelectronic industry relies upon the properties of semiconductor materials and, in particular, of silicon (Si); planar processing technology derives its success from the properties of thermally grown silicon dioxide (SiO_2), which features a reticular constant very close to that of silicon

Three dimensional representation of atoms position in a silicon crystal.

- A silicon crystal has the same periodical structure as diamond; each silicon atom has four valence electrons forming four covalent bonds with four neighbor atoms.
- The electrical characteristics of silicon can be modified by suitably adding impurities (P, As, B) with controlled concentration and growing thin oxide layers in well defined places; an integrated circuit also includes metal (Al, Cu) strips for device interconnection and silicon nitride for intermetal isolation

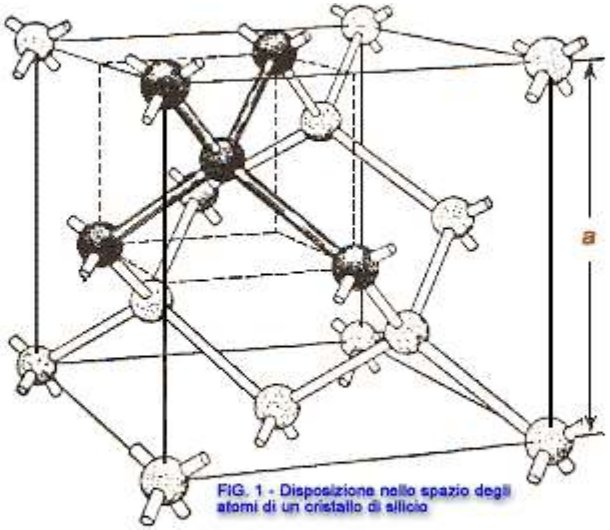
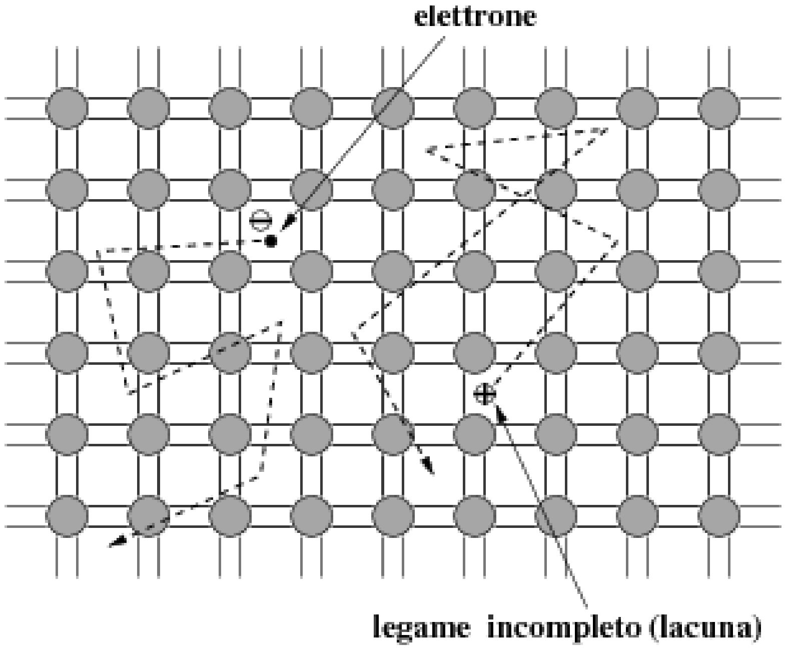


FIG. 1 - Disposizione nello spazio degli atomi di un cristallo di silicio

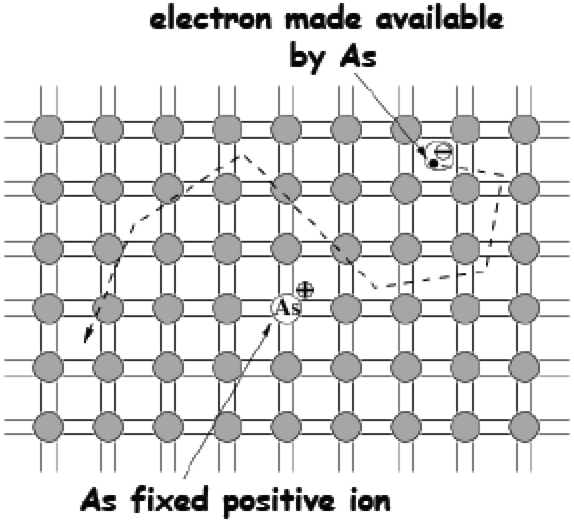
- **In intrinsic (i.e. pure) silicon, at room temperature, an electron can acquire energy due to thermal agitation and break free from a covalent bond, leaving behind an unbalanced positive charge unit in the atom it belonged to and an incomplete bond or hole (electron-hole generation).**
- **An electron from a neighbor atom can be attracted by the positive charge and fill the first hole (electron-hole recombination) while in turn leaving behind another hole (i.e. breaking the covalent bond it formed).**
- **This break (a covalent bond) and fill (a hole) mechanism can recur in such a way that a hole (and the associated unbalanced positive charge unit) can be carried around in the lattice, therefore behaving like a positive charge carrier; this mechanism is actually exploited to drive currents in electronic devices.**

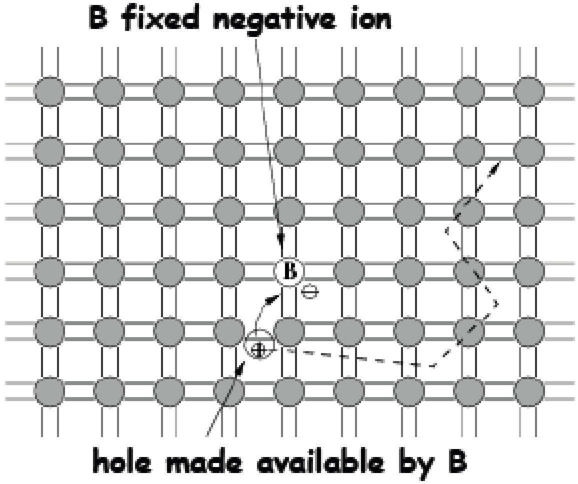


The electrical properties of silicon, in particular to enhance the concentration of free carriers, can be changed by the so called doping process, which involves adding impurities with a given concentration to the silicon lattice.

N-doping: increases the concentration of electrons by adding donor atoms (atoms of a pentavalent element like As or P), each donating an electron to the silicon lattice; an N-doped piece of silicon is called N-type silicon.

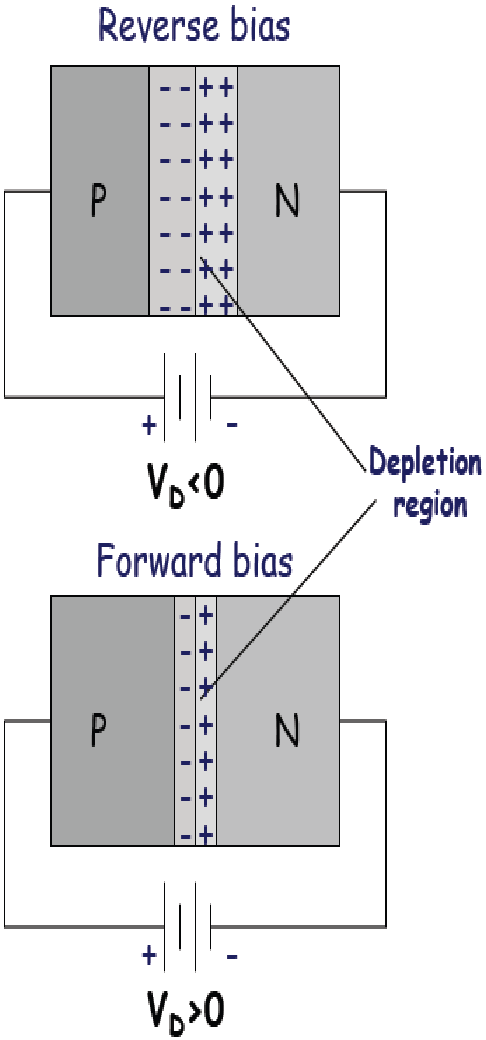
P-doping: increases the concentration of holes by adding acceptor atoms (atoms of a trivalent element like B), each accepting an electron from the silicon lattice; a P-doped piece of silicon is called P-type silicon.





PN junctions:

- ❑ **PN junctions are ubiquitous in semiconductor devices; they consist of two regions, one P-doped, the other one N-doped facing each other on a single silicon crystal.**
- ❑ **If the N side is biased at a higher potential than the P side, then the junction is operated in a reverse bias condition; a very small drift current flows from the N region to the P one; the depletion region (also called space charge region) gets wider.**
- ❑ **If the P side is biased at a higher potential than the N side, then the junction is operated in a forward bias condition; large hole and electron diffusion currents flood the N and P side respectively; the depletion region (also called space charge region) gets smaller.**

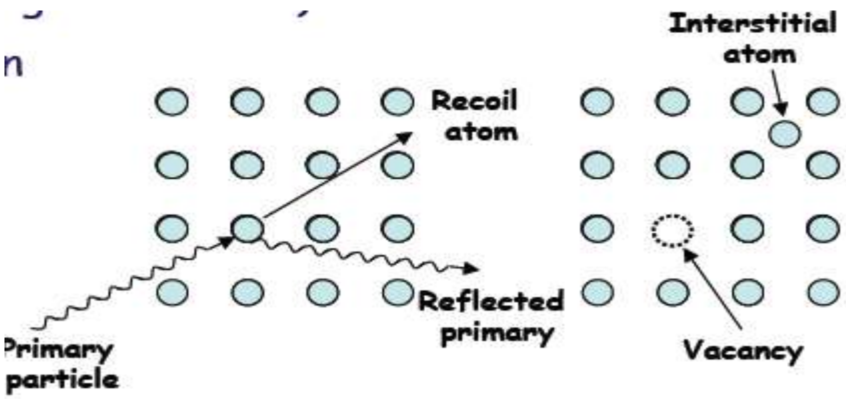


Basic damage mechanisms in semiconductor devices

Despite the complexity of the interaction processes and their dependence on the properties of the incident particle and of the target material, two are the basic radiation damage mechanisms affecting semiconductor devices.

Ionization damage: **takes place when energy deposited in a semiconductor or in** insulating layers, chiefly SiO2, frees charge carriers (electron-hole pairs), which diffuse or drift to other locations where they may get trapped, leading to unintended concentrations of charge and parasitic fields; this kind of damage is the primary effect of exposure to X- and γ-rays and charged particles; it affects mainly devices based on surface conduction (e.g. MOSFETs).

Displacement damage (DD): incident radiation dislodges atoms from their lattice site, the resulting defects altering the electronic properties of the crystal; this is the primary mechanism of device degradation for high energy neutron irradiation, although a certain amount of atomic displacement may be determined by charged particles (including Compton secondary electrons); DD mainly devices based on bulk conduction (e.g. BJTs, diodes, JFETs).



Displacement effect in a bidimensional crystal

Basic effects of radiation damage

❑ Effects of radiation in semiconductor devices can be included in one of two broad classes:

❑ **Total dose (TD) effects: are due to the progressive build-up of trapped** charge in insulating layers or at the Si/SiO2 interface (as a consequence of ❑ionization phenomena) or of defects in the bulk of the devices (originating from accumulation of displacement events).

❑ **Single event effects (SEE): are due to charge deposition induced by a single** particle that crosses a sensitive device region; the effects may lead to destructive or non-destructive damage of the device.

✓ SEEs occur stochastically, while TD is cumulative and may become visible after the device has been exposed to radiation for some time.

✓ TD is usually related to long term response of devices, whereas SEE is concerned with short time response.

✓ Only a tiny part of the device is affected by SEE, corresponding to the position of the particle strike, while TD uniformly affects the whole device, because it results from the effect of several particles randomly hitting the device.

✓ As far as SEE is concerned, the most important figure is the rate of occurrence; TD is characterized by the maximum drift of the main device parameters.

Ionization damage effects

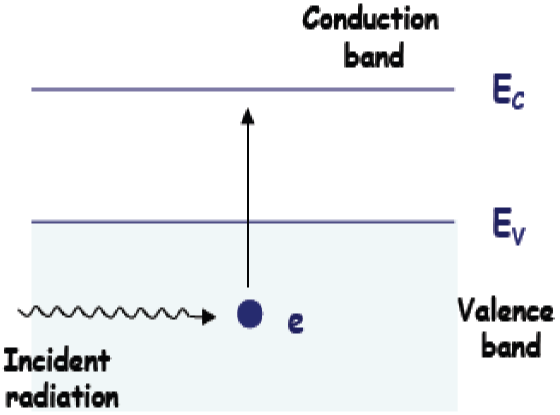
❑ As a consequence of the interaction with a charged particle or with a photon, electrons may get into an excited state, i.e. may go from the valence band to the conduction band through the band-gap leaving behind a hole.

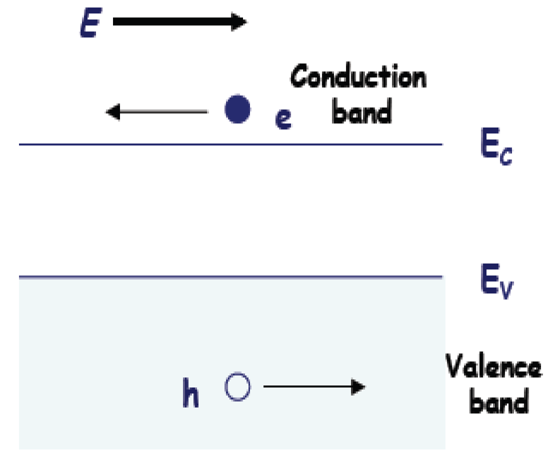
❑ In general, a single charged particle or photon (for example from a 60Co γ source) has enough energy to ionize many atoms along its track, therefore releasing electron-hole pairs with a certain linear density (3.6 eV/e-h are needed in Si, 17 eV/e-h in SiO2).

❑ The free electrons and holes may diffuse or drift (under the effect of an electric field) away from the generation point.

❑ After generation, carriers can

1. recombine
2. get trapped in defects
3. be collected at a device electrode





Ionization damage effects

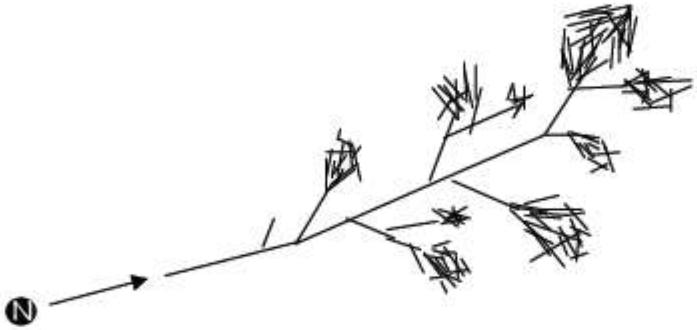
- Ionizing events may produce transient or permanent effects

- **Transient (or single event) effects:** **if an electric field is present in the region** where the interaction takes place and carriers are released, electrons and holes are separated and recombination is negligible; for instance, in a PN junction region, radiation interaction with silicon is responsible for current (or photocurrent) generation

- **Permanent (or total dose) effects:** **in isolating layers the number of generated** carriers and their mobility are smaller than in (intrinsic or doped) silicon; therefore no photocurrent can be observed; on the other hand, insulators (such as SiO2) and the interface between two layers of different materials (e.g. Si and SiO2) may feature a relatively high density of traps, where carriers (holes in particular) can get stuck; as a consequence of several subsequent ionizing events, trapped charge density increases together with the generated, parasitic field, which in turn may be responsible for a shift in the characteristic of the irradiated electronic devices

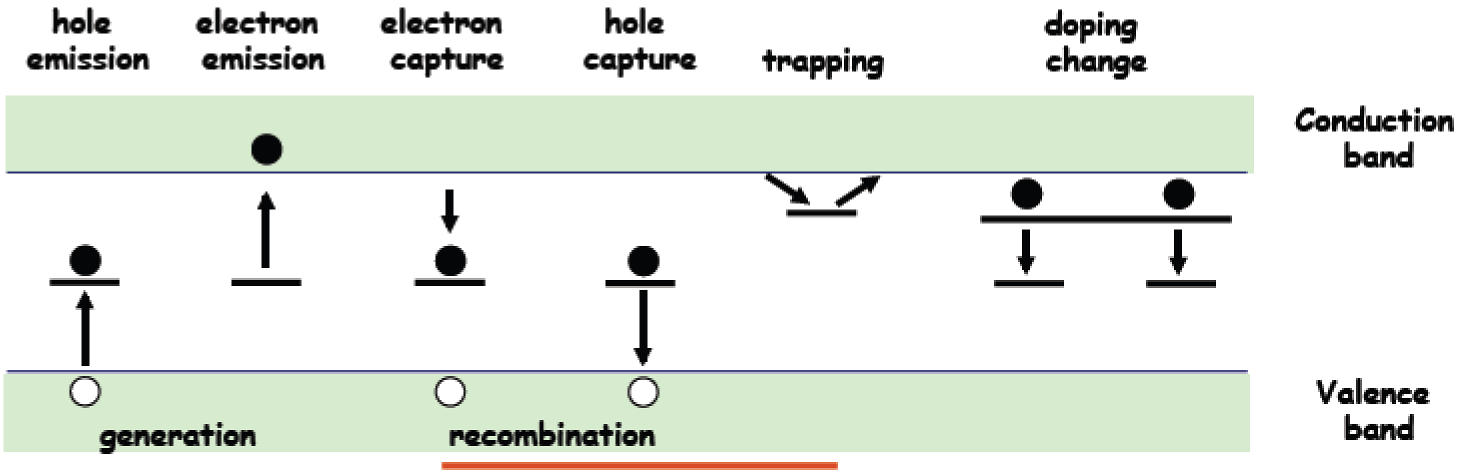
Dislocation damage effects:

- An impinging particle (e.g., a neutron) may interact with an atom and transfer to it enough energy to dislodge it from its position in the lattice (the minimum energy needed to dislodge a silicon atom is about 20 eV).
- The dislodged atom may travel a certain distance, possibly dislodging other atoms (a MeV neutron may transfer 60/70 keV to a lattice atom, which in turn may produce cluster defects by dislodging hundreds of atoms in regions a few hundred of nm in size).
- The created defects alter the crysta periodicity and are responsible for the formation of energy levels inside the band-gap; these energy levels alter the electrical properties of the material and of the electronic devices (e.g., minority carrier lifetime, carrier concentration, mobility)



Cluster defects in silicon lattice due to an impinging neutron

- ☐ **Displacement damage manifests itself in several ways.**
- ☐ **Formation of mid-gap states facilitates the transition of electrons and holes between bands; since transition probabilities are exponential functions of the energy difference, processes involving transitions between both bands require mid-gap states to proceed at an appreciable rate; whether recombination (electron and hole capture) or generation (electron and hole emission) dominates depends on the relative concentration of carriers and empty defect states; generation prevails in depletion regions, where the conduction band is underpopulated, increasing the reverse current in PN junctions; recombination prevails in forward biased junctions, where carriers flood the conduction band, resulting in charge loss and current decrease**



- Displacement damage manifests itself in several ways.
- **States close to the band edges facilitate trapping, where charge is captured** and released after a certain time.
- **Mid-gap states may capture electrons and holes from doping atoms (majority** carriers), therefore changing the doping characteristics of the crystal.
- **Defect states in the band-gap may act as scattering centers for charge** carriers and reduce their mobility; they can also facilitate defect-assisted tunneling of carriers through potential barriers, which is responsible, for instance, for the increase of the reverse current in PN junctions and of the leakage current in thin oxides.

Single event (transient) effects

- Single event effects are due to a single particle crossing the sensitive area of a device or circuit; some of these events are classified as soft, since they do not induce any physical damage, but only loss of information, such as a bit flip in a memory array; other events, such as the gate oxide rupture following the strike of a heavy ion, are termed hard, because they do induce permanent damage
- The main classes of soft effects are:
  - single event upset (SEU), the corruption of a single bit in a memory array
  - multiple bit upset (MBU), the corruption of multiple bits due to a single particle
  - single event transient (SET), a transient signal induced by an ionizing particle in a combinatorial or analog part of a circuit
- The main classes of hard effects are:
  - single event gate rupture (SEGR), rupture of gate oxide occurring especially in power MOSFETs
  - single event burnout (SEB), burnout of a power device
  - single event latch-up (SEL), the activation of parasitic bipolar structures, leading to a suddenincrease of the supply current

Single event upset (SEU)

- To cause disturbance in a circuit, the charge generated by a particle (a heavy ion) strike must be collected by a sensitive node; reverse biased pn junctions (semiconductor junctions with the p side at a lower potential than the n side) are the most likely candidate to collect charge, since they feature a large depletion region and a strong electric field
- In the case of a static RAM cell, the particle may strike the drain electrode of the off NMOSFET; the released charge is collected at the reverse-biased drain pn junction; the voltage at the struck node tends to decrease, turning the radiation-induced current into a voltage transient; the current decreases the potential at the drain node, possibly below the cell switching voltage, therefore changing the initial state

Multiple bit upset (MBU)

Single event effects have become more complex to study as the feature size of CMOS processes (the minimum length that can be obtained by the lithography), has been scaled down to the submicron realm

Radiation effects in JFETs

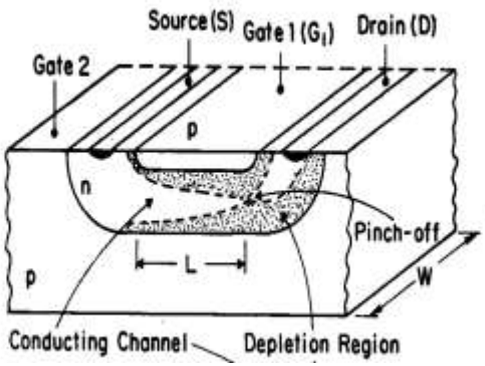
Operation of the JFET transistor:

❑ Operation of the junction field-effect transistor (JFET) is based on the transport of majority carriers (electrons in N-JFET and holes in the P-JFET) in the silicon bulk of the device; in the case of an N-type JFET.

❖ heavily doped N-type source and drain regions are fabricated at the two ends of the device channel, an N-type pocket featuring a much lower doping concentration.

❖ a (usually) shallow implanted P-well is used as the top gate terminal while the device substrate can act as the bottom gate terminal.

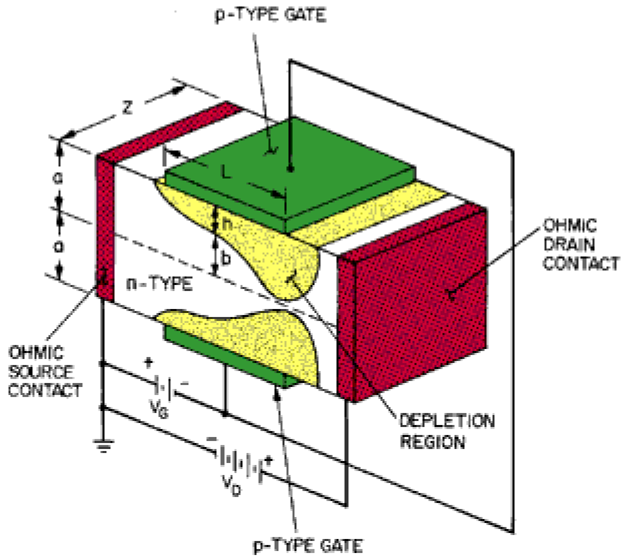
❖ when a reverse bias is applied at the (top and/or bottom) gate/channel junction, a depleted region is created; if a potential difference is applied between source and drain, by modulating the width of the depletion region, it is possible to control the channel section and, as a consequence the current flowing between the drain and the source



❑ As in the case of the MOSFET, the minimum value of the channel length L which can be achieved in a given technology is used to provide a measure of the lithographic limits of the fabrication process.

Radiation effects in JFET transistors:

- Since in JFET operation is based on the transport of carriers in the device bulk, junction FETs are much less insensitive to ionizing radiation than MOSFETs (no gate oxide nor channel at a Si/SiO2)



- Moreover, since the current flowing between the source and the drain is made of majority carriers, JFETs are also quite insensitive to degradation of the average lifetime of minority carriers; therefore JFETs can tolerate quite high neutron fluences, since the channel doping concentration is generally quite high (in the order of 1016 cm-3)
- On the other hand, dislocation damage can produce:
  - a sizeable increase in the gate leakage current (reverse current of a PN junction) due to increase in the carrier generation rate in the gate/channel depletion region
  - a considerable increase in the power spectral density of the noise due to the generation of lattice defect in the device bulk; they become active as generation/recombination centers when they are located in the depletion region and close to the channel; therefore their activity depends on the bias condition of the device (in particular on VGS)
- Depending on the device layout, also field oxide ionization may be responsible for some gate current increase

Effects of 60Co γ-rays on the gate current

❑ Exposure of junction FETs to γ-rays was proven to produce a significant increase in the device gate current

❑ As a general consideration, the detected increase in the gate current can result form one (or both) of the following effects

❖ atomic dislocation in the junction depletion region, where the resulting energy levels act as generation centers (recall that γ-rays from cobalt 60 may dislodge atoms from their location in the lattice through secondary Compton electrons)

❖ doping type inversion beneath the field oxide between source and drain due to positive charge Trapping

γ-rays and proton effects on the gate current

❑ In most cases, 60Co γ-rays just produces pure dislocation damage effect; this can be shown by taking a device parameter (the gate current) as the figure of merit of the technology with respect to the investigated radiation damage (displacement) and comparing the effects on that parameter of γ-rays and of another type of radiation (e.g., protons)

❖ in order to compare the displacement damage effect (expressed in terms of variation of the normalized gate current) due to protons and γ-rays, the NIEL (non ionizing energy loss) of each particle has to be known

❖ displacement damage dose can be calculated based on the particle fluence

❖ change in the gate current is found to be proportional to the displacement dose and independent of the particle type, thereby demonstrating that displacement damage predominates over ionization in γ-irradiated JFETs

Random telegraph signal (RTS) **waveforms in JFETs**

- ❑ RTS noise, also called burst noise, trapping noise or generation-recombination noise has been proved to result from the random capture and release of carriers at one or more localized electrical traps
- ❑ In an RTS signal, the current switches between two or more average levels in correspondence to every change of the occupation state of the traps
- ❑ RTS noise has been found in forward and reverse biased diodes, BJTs, in the drain current of JFETs and MOSFETs; a Lorentzian noise power spectral
- ❑density is associated to RTS noise