Design and Analysis of VLSI Subsystems

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Lecture - 01
Understanding Silicon

Silicon is an important material for developing the CMOS Transistor. There are a few precise properties of the silicon that characterizes the CMOS transistors. Before considering the phosphorous doped silicon atom structure. In a silicon crystal lattice, a silicon is present in the middle of the crystal lattice with the neighboring atoms of silicon which forms the covalent bond. The silicon density is around $5x10^{22}/cm^{3}$, that is in a block of $1cm^{3}$ there will be 10^{22} atoms of silicon. Apply a minimal electric field of 0.1 or 0.01 volts between the positive and negative potential. At room temperature, due to thermal energy there will be $1.4x10^{10}/cm^{3}$ of silicon atoms. In $1cm^{3}$ block, a 10^{10} bonds of silicon atoms forms with the neighboring atom will be broken. Thereby $1.4x10^{10}/cm^{3}$ bonds are broken and it produces 10^{10} free electrons or majority charge carriers. These free electrons are flowing towards the positive potential and hence there will be flow of current. But in $1cm^{3}$ of the silicon block 10^{10} electrons are present then the amount of current generated is very low and thus it is not useful for the circuit design applications. Therefore at-least 100 or 10's of microampere current is required to work on the design application. In this case, to improve the electrical conductivity in CMOS structure an external material is used know as dopants.

N-type Dopants:

Consider the N-type doping, the N represents the NMOS structure which consists of electrons or negative majority carrier as shown in figure 1.1. The n-type material has 5 valence electrons in its outermost shell such as phosphorous or arsenic which is an external material or external atom. If phosphorous is doped in certain manufacturing techniques like diffusion or implantation the resultant will be phosphorous diffused atom. Once diffusion process is completed, this single phosphorous diffusion inside the silicon atom structure forms the 4 covalent bonds with its neighboring silicon atoms. The 5th valence electron in phosphorous is attracted towards positive potential, whenever the bias is applied.

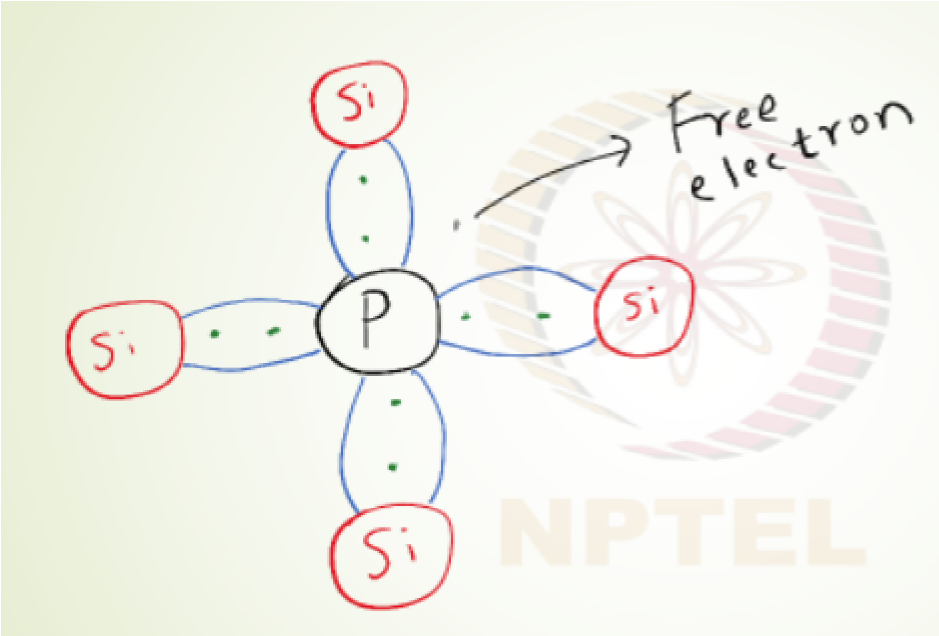

Figure 1.1: N-type dopants

If the number of phosphorous atoms is two, then there exist 2 free electrons and it's utilized for conducting the current. Similarly, if 10 phosphorous atoms are used then it consists 10 free electrons. Therefore, the phosphorous atom can have more than 10^{10} free electrons that can be designed for highly conductive transistor. This is one of the advantages in extracting more current from the silicon substrate.

One of the most important benefits of silicon is, it is easily available and highly utilized for the semiconductor circuits and systems. Henceforth the other different materials such as carbon and graphene semiconductor material will be used, but it's still under research process. But the semiconductor material like silicon is used widely and it can be doped easily.

Dielectric plays a major role in CMOS transistor. Silicon dioxide has a dielectric performed with the help of oxidation. The process of oxidation consumes some of the silicon atoms and forms silicon dioxide which is a simple process. Whereas the graphene-based oxide and carbon-based oxide doesn't form the dielectric.

These properties of silicon can be easily diffused inside the silicon atoms or the crystal lattice structure. Silicon dioxide is another benefit for silicon material. Obtaining a good conductivity material extracted from the silicon makes it widely popular as a semiconductor material. Hence the CMOS material or CMOS design or VLSI design is highly dependent on the silicon material.

P-type Dopants:

Considering the p-type dopants is formed by doping a pure silicon crystal with impurity atoms having three valence electrons and one hole as shown in figure 1.2. The elements used is boron, gallium and indium. If boron is diffused or implanted inside the silicon crystal lattice structure, it still forms the four covalent bonds, since silicon has four valence electrons. As boron atom has one valence electron less but still it forms a covalent bond as a hole and it's also called as mobile hole. Once the bias is applied, the positive carriers which is holes are moving towards the negative potential and hence it is called as P-type doping. Whereas in N-type doping, the negative carriers which is electrons are moving towards the positive potential. P-type dopants gives positive majority carriers and N-type doping gives negative majority carriers. Intrinsic concentration means it is the pure silicon material and it cannot be doped.

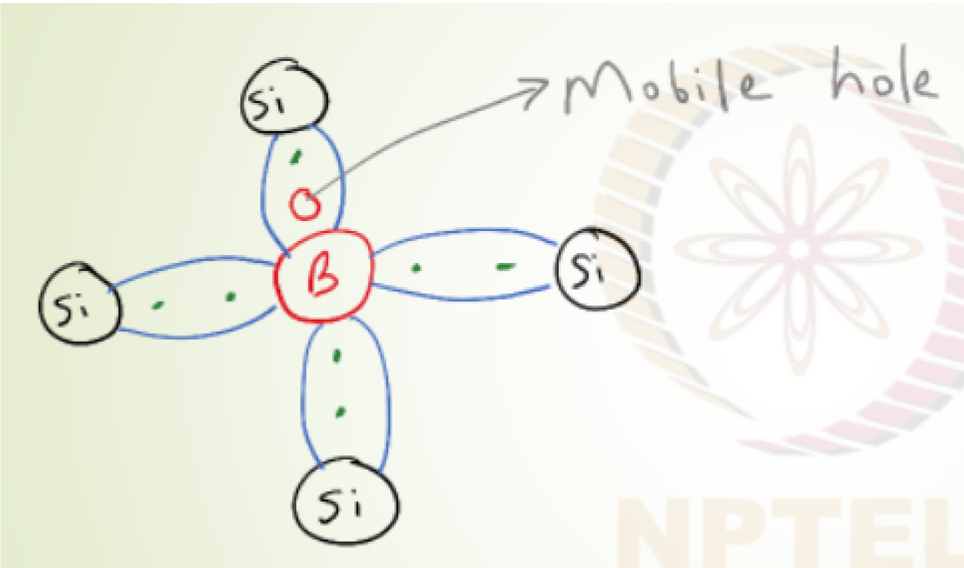

Figure 1.2: P-type dopants

As indicated earlier, 1-hole acts like a majority carrier. So, if 10 boron atoms are introduced then there will be 10 such holes introduced into a silicon structure. Thereby 10^{10} such hole concentration is present inside $1cm^3$ of silicon lattice structure, this majority carriers can be used to constitute the current from semiconductor material.

Biasing Condition:

In N-type doped silicon structure, phosphorous has 5 valence electrons and silicon has 4 valence electron this forms the 4 covalent bonds and it has one free electron. When a bias is applied between positive and negative terminal, the free electron is moved towards the positive side as shown in figure 1.3.

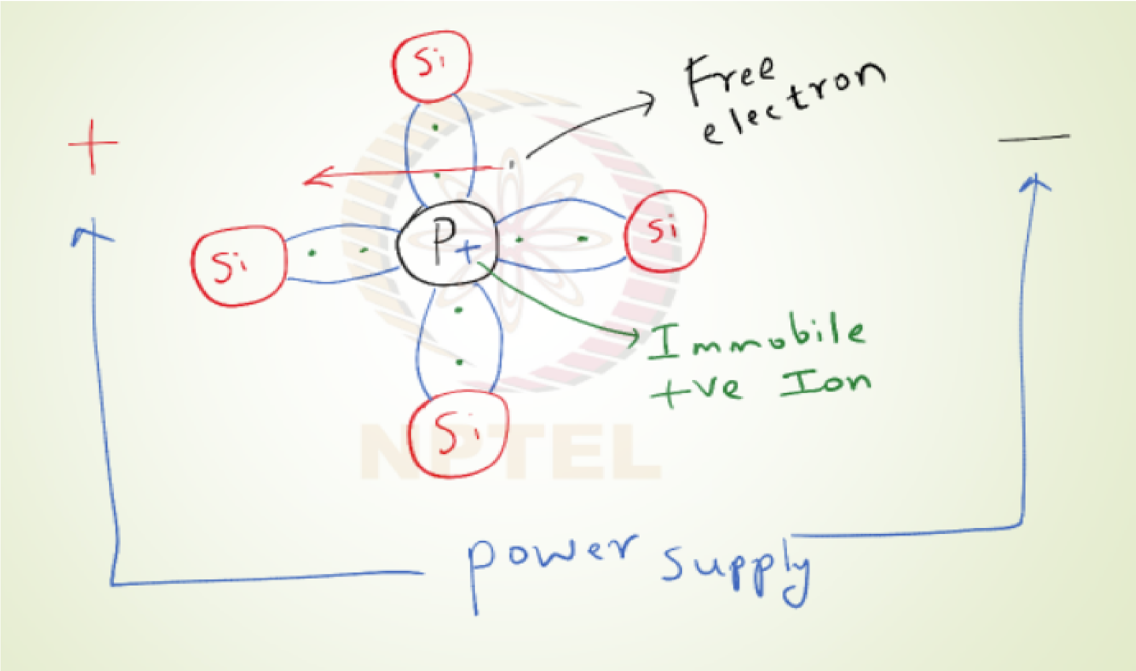

Figure 1.3: N-type: movement of free electrons when biased

Earlier phosphorous has 5 electrons outside the shell and 5 protons inside the shell, once the free electrons move away the phosphorous as 4 valence electrons outside shell and 5 protons inside shell is present. Thereby this particular phosphorous atom is not electrically neutral anymore. This phosphorous atom acts as a positive charge ion or phosphorus ion, that is whenever the atoms become electrically charge then it’s called as an ion. Because ion is an atomic structure, as it is not mobile it is also known as immobile positive phosphorous ion.

Similarly in P-typed silicon structure, bias is applied between positive and negative terminal the holes are moved towards the negative terminal as shown in figure 1.4. As the holes are moving away the electrons in the neighboring covalent bond starts hopping into this particular hole space, thereby it creates the hole in same space. Before biasing, boron atom has become electrically neutral atom because it has 4 valence electrons outside the shell and 3 protons inside the shell once bias is applied the boron atom as 3 valence electrons outside the shell and 3 protons inside the shell. Thereby this atom is no more electrically neutral and it is an immobile negative ion.

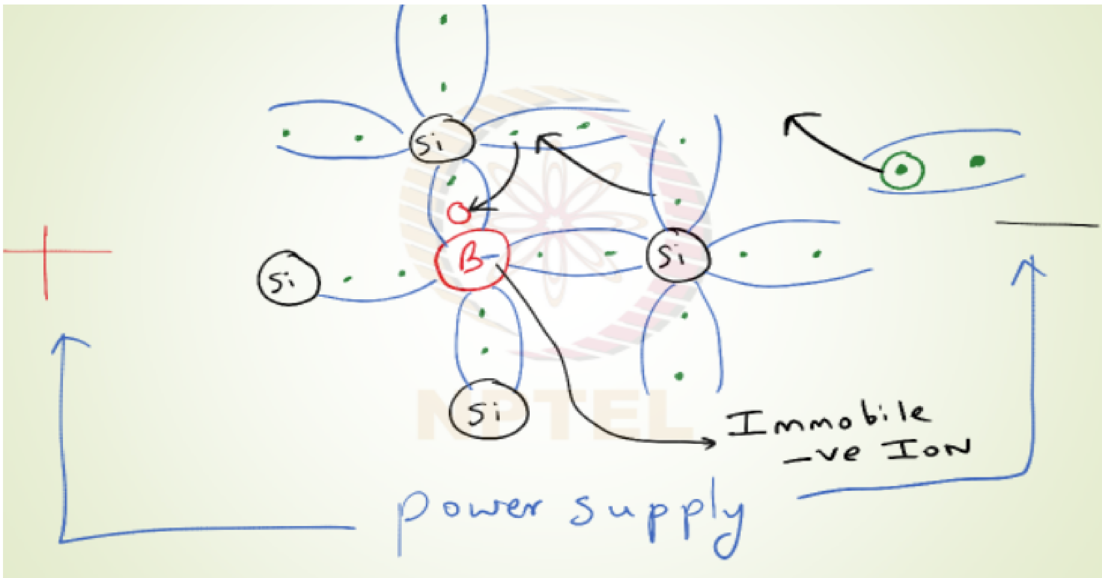

Figure 1.4: P-type-movement of mobile holes when biased

From the table 1.1 of doping concentration, N_D and N_A represents the concentration. The concentration is always expressed in-terms of per unit volume. So, this is diffused into a block of silicon volume for $1cm^3$. As we know in $1cm^3$ silicon block there will be $5x10^{22}$ atoms of pure silicon. For the bulk silicon, consider a $1cm^3$ block there will be $5x10^{22}$ atoms. But in this particular bulk silicon, if the diffusion or implantation process takes place, then there exists a dopant inside the silicon bulk structure. Once the diffusion process is completed, still $5x10^{22}$ atoms of silicon are present in addition to this a dopant concentration is present. So, the overall process is actually characterized in terms of how many numbers of dopant are been introduced in one centimeter cube of the silicon structure. Due to this, doping concentration is represented in terms of per centimeter cube.

Table 1.1: Doping representation

Representation	N_D or N_A
N^{--} or P^{--}	$< 10^{14}/cm^3$
N^{-} or P^{-}	$< 10^{16}/cm^3$
N or P	$< 10^{18}/cm^3$
N^{+} or P^{+}	$< 10^{20}/cm^3$
N^{++} or P^{++}	$> 10^{20}/cm^3$

The maximum doping concentration can be represented up to 10^{21}, but it cannot be more than 10^{21} since it destabilizes the overall silicon structure. The minimum doping concentration can be considered up to 10^{10}. Therefore, the doping concentration can be represented between the range from 10^{10} to 10^{21}. From table doping concentration for $10^{14}/cm^{3}$ is represented as N^{--} and P^{--}. For example, the phosphorous or arsenic atom with 10^{13} is diffused inside the silicon lattice structure of $1cm^{3}$, then it is represented as N^{--} for phosphorous and P^{--} for boron.

Similarly, if the dopant concentration is somewhere between 10^{14} to less than 10^{16} then it is represented as N^{-} and P^{-}. If its between 10^{16} to less than 10^{18} then it is represented as N^{+} and P^{+} and for greater than 10^{18} then it is represented as N^{++} and P^{++}.