5.2 SINGLE ELECTRON PHENOMENA

Theory

- Transistors used in many electronic devices.
- Transistors are also used in transferring and amplifying the signals.
- Single-atom and single-electron transistors are available and they are used in sensitive amplifiers, electrometers, switches, oscillators and other digital electron circuits.
- All these instruments will be operated by using single electrons or quantum dots.
- For single electron phenomena to occur, we have to keep the single electron or quantum dot in isolation.
- There are two rules for preventing electrons from tunneling back and forth from a quantum dot.
- When we follow these rules, they help to ensure that the dot remains isolated and quantized.
- The rules are, **Rule 1:** The coulomb Blockade **Rule 2:** Overcoming uncertainty

Rule 1: The coulomb Blockade

- We know that the coulomb blockade can prevent unwanted tunneling.
- Hence we can keep the quantum dots isolated.

The condition for this is given by, $E_C = \frac{e^2}{2C_{dot}} >> K_B T \qquad ------(1)$

Rule 2: Overcoming uncertainty

- For the second condition, to keep quantum dots electronically isolated, we look to the uncertainty principle.

According to uncertainty principle, $\Delta E_C \, \Delta t = h \qquad -------(2)$

Energy uncertainty, $\Delta E_C = \frac{h}{\Delta t} \qquad -------(3)$

- Here, h is the Planck's constant and 'Δt' is the measurement time. Since, quantum dot is a tiny capacitor then the measurement time 'Δt' is capacitor's time constant.
- The time constant for a capacitor is RC, where R is the resistance and C is the capacitance.

∴ We can write the time constant as, $\Delta t = R_t C_{dot}$ $\quad ------- (4)$

Substituting equation (4) in equation (3), we get,

$$\Delta E_C = \frac{h}{R_t C_{dot}} \qquad ------- (5)$$

Where, R_t → tunneling resistance & C_{dot} → capacitance dot.

For maintaining electron isolation in quantum dot, we need

$$\Delta E_C < E_C \qquad ------- (6)$$

Substituting equation (3) and equation (1) in equation (6), we get,

$$\frac{h}{\Delta t} < \frac{e^2}{2C_{dot}} \qquad ------- (7)$$

Substituting equation (4) in equation (7), we get,

$$\frac{h}{R_t C_{dot}} < \frac{e^2}{2C_{dot}} \qquad ------- (8)$$

In other words we can write the equation (8) as,

$$R_t >> \frac{h}{e^2}$$

Substituting the values for $h = 6.625 \times 10^{-34}$Js and $E = 1.6 \times 10^{-19}$C , we get

$$\frac{h}{e^2} = 25878\ \Omega \text{ is the resistance quantuam}$$

- This high resistance value is like a thick insulating material surrounding the quantum dot.
- Thus, we keep the quantum dots electronically isolated.

Conditions for tunneling

- The two tunneling conditions are

1. $\frac{e^2}{2C_{dot}} >> K_B T$ and 2. $R_t >> \frac{h}{e^2}$

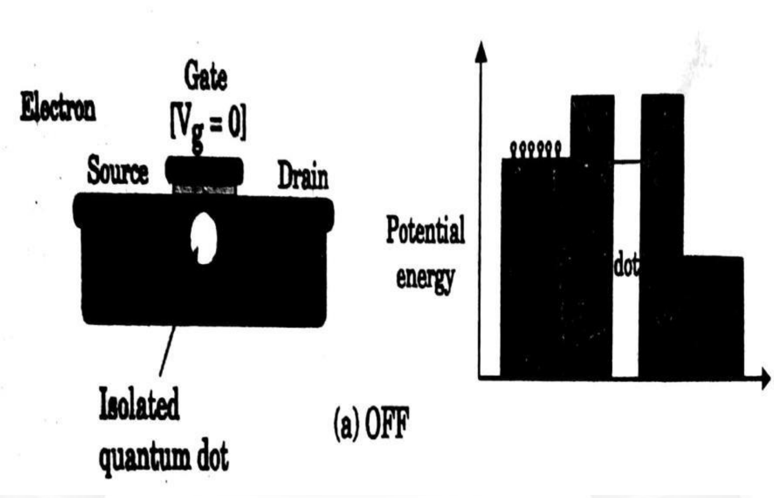
- The current jumps in increments every time the voltage changes by the value of equation

$$\Delta V = \frac{e}{C_{dot}}$$

- This is called coulomb blockade because the electrons are blocked from tunneling except at the discrete voltage change positions.
- The two conditions or rules which explain the single electron phenomenon will help to build a single electron transistor.

SINGLE ELECTRON TRANSISTOR (SET)

Definition: A transistor made from a quantum dot that controls the current from source to drain one electron at a time is called single electron transistor.



(a) OFF

Working of single electron transistor (SET)

A generalized schematic device and its operation is shown in the above figure.

1. The SET has an electrically isolated quantum dot located between the source and drain.
2. When the SET is in "OFF" mode, the potential energy diagram shows that it is not energetically favorable for electrons in the source to tunnel to the dot.

3. The purpose of SET is to control the tunneling of electrons into and out of the quantum dot.
4. To do this, we first apply the correct circuit geometry and materials.
5. To control tunneling, we apply a voltage bias to the gate electrode.
6. When the SET in “ON” mode, electrons tunnel one at a time via the dot, from source to drain as shown in figure.
7. This is because the gate voltage creates an electric field and enables current to flow in from source to drain.
8. Applying a voltage, the gate in SET creates an electric field and change the potential energy of the dot with respect to the source and drain.
9. This gate voltage controlled potential difference can make electrons in the source attracted to the dot
10. Once the electron is on it, the dot’s potential energy rises as shown in figure.
11. The electron then tunnels through the Coulomb blockade on the other side to reach the lower potential energy at the drain as shown in figure.
12. With the dot empty, the potential lower again and the process repeats as shown in figure
13. For current to flow, this potential difference must be at least large enough to overcome the energy of the coulomb blockade.
14. The energy *‘E’* needed to move a charge *‘Q’* across a potential energy difference, *‘V’* is given by,

$$E = VQ$$

Here, $Q = e \rightarrow$ charge of an electron

$$\text{Hence, we can write, } V = \frac{E_C}{e} = \frac{\frac{e^2}{2C_{dot}}}{e}$$

$$= \frac{e}{2C_{dot}} \qquad -------(1)$$

Difference between ordinary and single electron transistor

- The single electron transistor (SET) is built like a conventions FET.
- The difference is that instead of a semiconductor channel between the source and drain electrodes, there is a quantum dot.
- This dot can be a particle on an insulating surface, a disk sandwiched between insulators or even just a section of semiconducting material where electric fields effectively isolate electrons.