

# Silicon n-p-n Cold Emission Cathode

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## Abstract

A study of a silicon n-p-n structure used as a cold emission cathode. Such a device is able to emit electrons in low external field and also to internally control the intensity of emission.

## 1 Introduction

The use of a semiconductor p-n junction in reverse bias as a cold emission cathode was proposed from around 1960 and some experiments were carried in the coming years. In initial experiments a silicon junction diagonally cut and reverse biased at breakdown was used. This produced some electron emission but with very low current efficiency. Later when ionic implantation become available, shallow junctions parallel with the surface were used with improved efficiency but still too low for most practical applications. In both cases the junction was reverse biased at breakdown in order to generate electrons and gaps inside the junction to be accelerated by the junction field barrier and part of the electrons to be emitted in vacuum. However, as we will see later on, some significant problems arise with this working conditions. The generated electrons benefit only partly by the field barrier due to the location where they are generated that is inside the barrier zone. The high reverse current create high level of spatial charge in the area and this compromise the electron acceleration. Also the breakdown current is not uniformly distributed over the junction area, but tend to be concentrated in some spots, this lead to strong local warm up and possible junction damage.

A different work arrangements can be used to address these problems, first the use of two junctions, one for electron acceleration working in reverse bias

but below breakdown voltage and a second one used for electron injection with the purpose to feed the first junction with electrons to be accelerated. In addition special measures must be taken to avoid the build up of spatial charge inside the barrier zone, charge which can seriously compromise the emission process.

## 2 Fundamental Structure of Cathode

A n-p-n cathode consists of two p-n junctions, the acceleration junction which is close to the emission surface and parallel with it and the injection junction which lay below the acceleration junction. The way in which the emission current is controlled is similar with the way in which the collector current is controlled in the bipolar transistor.

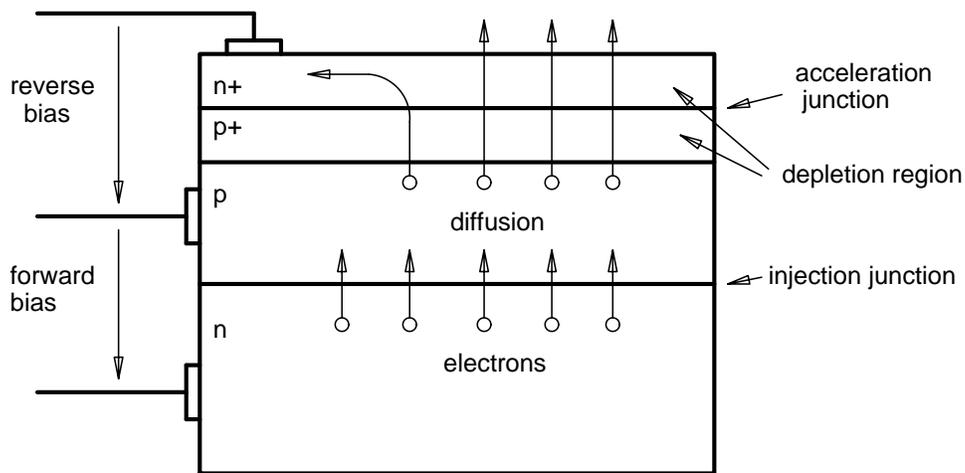


Figure 1: Structure of a p-n junction cathode

Ideally the n+ and p+ regions of the acceleration junction are completely depleted of majority carriers and occupied by the barrier zone. The high level of doping present in the n+ and p+ regions will produce a thin barrier zone and a strong electric field will be present in it. Also complete depletion will prevent the p+ region carriers to disseminate into the neighboring p region

and the resultant field to oppose the incoming electrons diffusion into the acceleration junction. To obtain the maximum acceleration the thickness of the n+ and p+ regions must be equal with the thickness of the depletion region at the reverse bias of operational voltage.

After acceleration, the electrons which arrive at surface with an energy higher or equal with the surface electron affinity, will be able to escape into vacuum. In the case of a semiconductor surface the electron affinity will be equal with the energy thickness of the conduction band. For this to happen we need that the potential of the barrier zone to be higher than the sum between the electron affinity of the used semiconductor and the energy losses sustained by the electrons while they move through the barrier zone to the surface. Also in addition to this, the necessary potential of the barrier must be bellow the breakdown potential of the junction. To reduce the energy losses sustained by the electrons through collisions with the crystalline lattice, the barrier zone of the acceleration junction must be thin and this result in the high level of doping in these regions.

The strong electric field of the barrier zone will accelerate the minority electrons from the edge between the barrier zone and the neutral p zone which lay bellow it. At equilibrium the concentration of minority electrons from the p zone is very low, this lead to a very low, near to zero, electron emission in the absence of any phenomena to increase the concentration of minority electrons. This very low residual emission can be further reduced down to zero by reduction of the reverse bias of the acceleration junction. To increase the electron emission we need to rise the minority electrons concentration in the p zone and the easiest way to do this is through injection from the nearby junction. This will represent the primary mechanism to control the intensity of emission.

Unlike the bipolar transistor where a high collector/base current ratio is highly desirable, here the n/p doping ratio of injection junction and the tickness of the p region are not so critical.

### **3 The Acceleration Junction**

If we note with  $V_B$  the total voltage over the barrier zone and with  $V_{B0}$  and  $V_R$  the internal barrier voltage in the absence of external bias and externally applied reverse voltage respectively, then the following conditions must be

fulfilled

$$V_B = V_{B0} + V_R > \frac{W_A}{q_e} \quad (1)$$

respectively

$$V_B < V_{BBR} \quad (2)$$

where  $W_A$  is the electron affinity,  $q_e$  is the electron elementary charge,  $V_{BBR}$  is the total breakdown voltage of the barrier.

In figure 2 the energy levels in the barrier zone are shown, in the absence and presence of reverse bias.

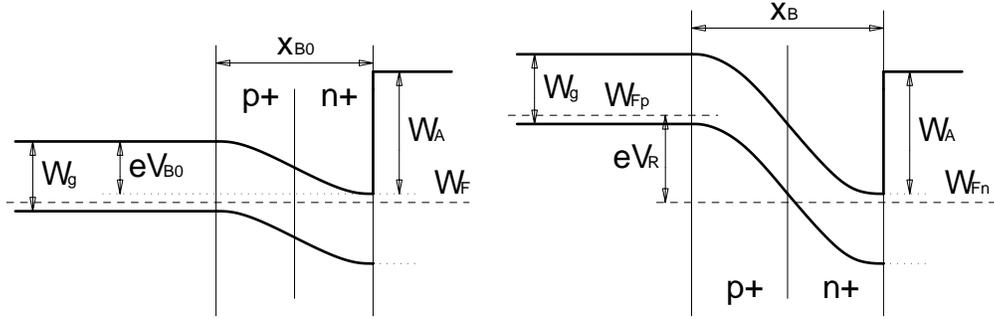


Figure 2: Junction energy levels

Considering that  $N_A$  and  $N_D$  are the concentration of ionized donors and acceptors from the n+ and p+ regions, the tendency for electrical neutrality will lead to

$$N_A x_p = N_D x_n \quad (3)$$

valid in the condition of full depletion approximation, which is the case for a junction that is thin and abrupt. Considering the junction flat, the electric field will have values only on the direction of x axis perpendicular on the junction plane. In this context we have

$$\frac{dE_x}{dx} = -\frac{d^2V}{dx^2} = \frac{\rho}{\varepsilon} \quad (4)$$

where  $V$  is the electric potential,  $\rho$  is the density of charge and  $\varepsilon$  is the semiconductor permittivity. For the density of charge in the depleted regions n+ and p+ we have

$$\rho_p = -q_e N_A \quad (5)$$

$$\rho_n = q_e N_D \quad (6)$$

The electric field must be 0 at the limits  $x = -x_p$  and  $x = x_n$  .

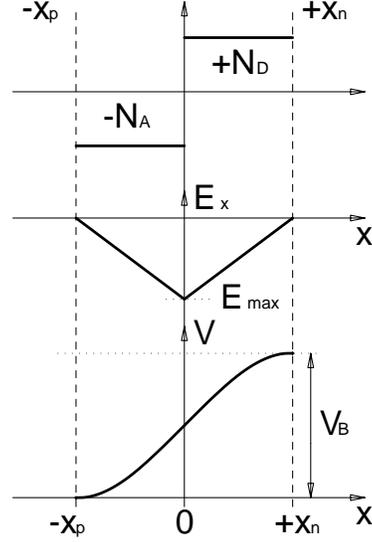


Figure 3: The junction field and potential

After integration and taking into account the conditions at limits, we have for electric field in the p+ and n+ zones

$$E_{xp}(x) = -\frac{q_e N_A}{\epsilon} (x_p + x) \quad (7)$$

respectively

$$E_{xn}(x) = -\frac{q_e N_D}{\epsilon} (x_n - x) \quad (8)$$

The electric field will have the maximum value in the junction plane at  $x = 0$

$$E_{max} = -\frac{q_e N_A}{\epsilon} \cdot x_p = -\frac{q_e N_D}{\epsilon} \cdot x_n \quad (9)$$

The electric potential drop over the two zones will be

$$V_p = \frac{q_e N_A}{2\epsilon} \cdot x_p^2 \quad (10)$$

respectively

$$V_n = \frac{q_e N_D}{2\epsilon} \cdot x_n^2 \quad (11)$$

The total voltage drop over the junction barrier zone will be

$$V_B = V_{B0} + V_R = V_p + V_n = \frac{q_e}{2\varepsilon}(N_A x_p^2 + N_D x_n^2) \quad (12)$$

With these the electric potential function of  $x$  will be

$$V_p(x) = \frac{q_e N_A}{2\varepsilon}(x_p + x)^2 \quad (13)$$

respectively

$$V_n(x) = V_B - \frac{q_e N_D}{2\varepsilon}(x_n - x)^2 \quad (14)$$

If we consider the thickness of the barrier zone as  $x_B = x_p + x_n$  then from (3) and (12) we have

$$x_B = \sqrt{\frac{2\varepsilon V_B (N_A + N_D)}{q_e N_A N_D}} \quad (15)$$

and for total barrier voltage

$$V_B = \frac{q_e}{2\varepsilon} \cdot x_B^2 \cdot \frac{N_A N_D}{N_A + N_D} \quad (16)$$

The thickness of the two depleted zones will be

$$x_p = x_B \cdot \frac{N_D}{N_A + N_D} \quad (17)$$

respectively

$$x_n = x_B \cdot \frac{N_A}{N_A + N_D} \quad (18)$$

From (16), (17), (18) and (9) we can write for the maximum field

$$E_{max} = \frac{2V_B}{x_B} \quad (19)$$

Because the junction will be symmetric having almost equal doping levels for n+ and p+ zones we have the condition  $N_A = N_D = N_i$ , with this the equations become

$$x_{BS} = \sqrt{\frac{4\varepsilon V_B}{q_e N_i}} \quad (20)$$

and

$$V_B = \frac{q_e N_i}{4\varepsilon} \cdot x_{BS}^2 \quad (21)$$

The electrons moving through the barrier zone will receive kinetic energy from the electric field present here, but in the same time they will lose energy due to the interactions with the crystalline lattice. Their total energy gained from the barrier field will be  $q_e V_B$ . Their final energy when they hit the surface is dependent by the balance between this gain and the loss of energy.

### 3.1 The Energy of Electrons

In their movement through the barrier zone the electrons will interact with the atoms from the crystalline lattice as well as with other electrons, ions, impurities and defects. As a result of these interactions, the electrons will be scattered from their original motion direction, scattering that leads to a change in momentum and energy of the electron. In the case of our acceleration junction, the barrier zone is depleted of electrons and the monocrystalline semiconductor is being characterized by a low number of defects and neutral impurities. Also the density of moving electrons is relatively low. In these conditions we can neglect the electron-electron scattering and also the scattering on defects and neutral impurities. Scattering on ionized impurities is important at low temperature, but with the increase of electrons energy it will decrease rapidly and for hot electrons it can be neglected in comparison with the scattering on lattice.

In our case the predominant scattering will be on lattice thermal vibrations that will produce electron-phonon scattering, the electron momentum and kinetic energy will have different scattering rates. If we consider an electron which received a momentum and energy in one direction, the time interval for this directional movement to become chaotic due to scattering, represents the momentum relaxation time  $\tau_m$ . In a similar way, the time interval for the electron energy (due to both directional and chaotic movement) to decrease to the lattice average thermal energy, represents the energy relaxation time  $\tau_e$ . For hot electrons in Si the momentum relaxation occurs much more rapidly than energy relaxation. This means that the accelerated electrons lose their directional movement quite fast, but retain their energy in the form of chaotic movement for a longer time.

The momentum relaxation time is related with the mean free path through  $\lambda = v_e \tau_m$ . If the mean free path is much longer than the barrier zone, then most of the hot electrons will hit the surface with the accumulated kinetic energy and a movement directed toward the surface, in this situation their kinetic energy works against electron affinity and contributes to emission. If

the mean free path is much shorter than the barrier zone, then the electrons lose their directional movement to chaotic movement but are still hot. If we consider that the energy distribution of this electronic gas is close to a Maxwell-Boltzmann distribution, then we have an effective electrons temperature related with the average energy through the typical equation

$$w_{th} = \frac{3}{2}kT_e \quad (22)$$

When the electrons reach the surface they will have a negligible directional movement and an elevated electrons temperature. Because the energy will be equally distributed on all the three degrees of freedom, on x direction normal on surface, the energy will be

$$w_{xth} = \frac{1}{2}kT_e \quad (23)$$

Also in this case only half of the electrons near surface will move toward the surface, the other half move away from the surface. If the mean free path is comparable with the barrier zone then when the electrons will reach the surface they will have a combination of directional movement toward the surface and chaotic thermal movement. This is happening because the electrons receive the energy and momentum from the electric field gradually while they pass through the barrier zone and the momentum received closer to the surface is less affected by the scattering.

Two types of phonons will contribute to electrons scattering, the acoustic phonon and the optical phonon. We can write for electron energy

$$w = \frac{(\hbar\kappa)^2}{2m_n} \quad (24)$$

where  $\hbar\kappa$  is the electron crystal momentum. We use the calculations of electron-phonon scattering presented in [1]. For Si at the lattice temperature  $T_0 = 300$  K we have the following parameters:  $D_A = 1.44 \cdot 10^{-18}$  V,  $D_o = 17.6 \cdot 10^{-9}$  V/m,  $c_s = 9000$  m/s,  $m_n = 0.32 \cdot m_e = 2.915 \cdot 10^{-31}$  kg,  $\omega_0 = 99.4 \cdot 10^{12}$  1/s,  $\rho = 2328$  kg/m<sup>3</sup>. Momentum relaxation time due to scattering on the acoustic phonon is

$$\tau_{mA} = \frac{\pi\hbar^3\rho c_s^2}{D_A^2 k T_0 m_n \kappa} = \frac{\pi\hbar^4\rho c_s^2}{D_A^2 k T_0 m_n^{3/2}} \cdot \frac{1}{\sqrt{w}} \quad (25)$$

Momentum relaxation time due to scattering on the optical phonon is

$$\tau_{mo} = \frac{\pi \hbar^3 \rho \omega_0^2}{D_o^2 k T_0 m_n \kappa} = \frac{\pi \hbar^4 \rho \omega_0^2}{D_o^2 k T_0 m_n^{3/2}} \cdot \frac{1}{\sqrt{w}} \quad (26)$$

Energy relaxation time due to scattering on the acoustic phonon is

$$\tau_{eA} = \frac{\pi \hbar^3 \rho}{2 D_A^2 m_n^2 \kappa} = \frac{\pi \hbar^4 \rho}{2 \sqrt{2} D_A^2 m_n^{5/2}} \cdot \frac{1}{\sqrt{w}} \quad (27)$$

Energy relaxation time due to scattering on the optical phonon is

$$\tau_{eo} = \frac{\pi \hbar^3 \rho \kappa}{D_o^2 m_n^2} = \frac{\sqrt{2} \pi \hbar^2 \rho}{D_o^2 m_n^{3/2}} \cdot \sqrt{w} \quad (28)$$

If we compute the ratio for momentum relaxation

$$\frac{\tau_{mA}}{\tau_{mo}} = \frac{c_s^2 D_o^2}{D_A^2 \omega_0^2} \simeq 1.225$$

we can observe that both the acoustic and the optical phonon have a significant influence over the combined momentum relaxation time, as follow

$$\frac{1}{\tau_m} = \frac{1}{\tau_{mA}} + \frac{1}{\tau_{mo}} \quad (29)$$

and

$$\tau_m = \frac{\pi \hbar^4 \rho c_s^2 \omega_0^2}{k T_0 m_n^{3/2} (D_A^2 \omega_0^2 + D_o^2 c_s^2)} \cdot \frac{1}{\sqrt{w}} \quad (30)$$

The mean free path is related to the momentum relaxation time through the electron velocity from both thermal and directional movement

$$v_e = \sqrt{\frac{2w}{m_n}} \quad (31)$$

and we have

$$\lambda = \tau_m v_e = \frac{\sqrt{2} \pi \hbar^4 \rho c_s^2 \omega_0^2}{k T_0 m_n^2 (D_A^2 \omega_0^2 + D_o^2 c_s^2)} \quad (32)$$

which is independent of energy and for  $T_0 = 300$  K is 63.8 nm. This is comparable with the tickness of the barrier zone. The energy relaxation lenght due to scattering on the acoustic phonon will be

$$\lambda_{eA} = \tau_{eA} v_e = \frac{\pi \hbar^4 \rho}{2 D_A^2 m_n^3} \quad (33)$$

which is also independent of energy and at 300 K is 8.8  $\mu\text{m}$ . The energy relaxation length due to scattering on the optical phonon will be

$$\lambda_{eo} = \tau_{eo} v_e = \frac{2\pi\hbar^2\rho}{D_o^2 m_n^2} \cdot w \quad (34)$$

which is dependent of energy and for an electron energy of 1 eV it will be 990 nm. This is much shorter than  $\lambda_{eA}$  which indicate that at relatively low energy the optical phonon dominate the energy relaxation process.

(continuation...)

## References

- [1] Hot Electrons in Silicon Devices, G. Streutker, 1993, Eindhoven University of Technology