DESIGN OF A *pn* JUNCTION DIODE

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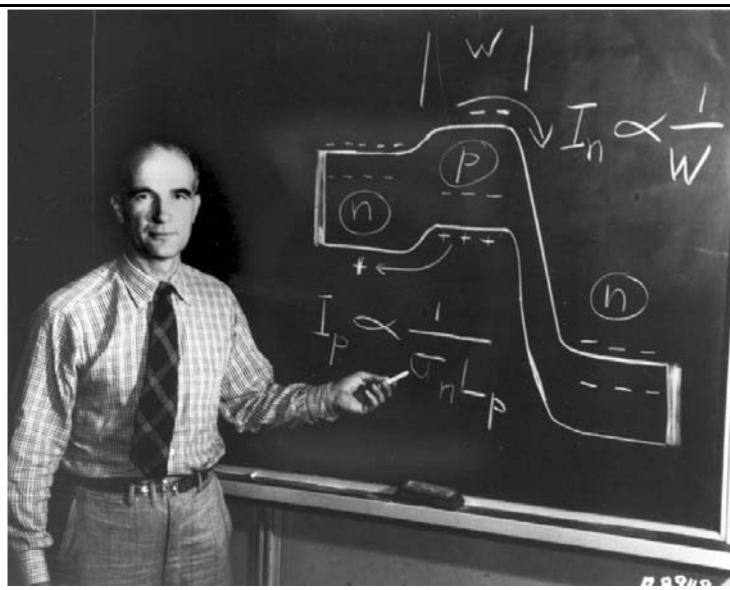
"One of the most striking things I've seen recently is the possibility of using gallium arsenide lasers and optical fibers in new transmission systems. Now you may observe that lasers and fibers will accomplish the same sorts of things as existing technology. But that's exactly what the transistor did: replaced the vacuum tube but at tremendous advantages in cost, power, space and reliability."

William Shockley, March 1975
(Nobel Laureate, 1956
as quoted by M. Sparks, Lester Hogan and J. Linville
in Physics Today, June 1991, p. 132)



William Shockley shared the 1956 Nobel prize with John Bardeen and Walter Brattain for their invention of the transistor.
(Courtesy of Bell Labs, Lucent technologies)

$$J = \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a} \right) n_i^2 \left[\exp\left(\frac{eV}{kT} \right) - 1 \right]$$

1. Preamble

The *pn* junction forward current density J in a long diode is generally described by the Shockley equation,

$$J = \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a}\right) n_i^2 \left[\exp\left(\frac{eV}{kT}\right) - 1\right] \tag{1}$$

where e is the electronic charge, k is Boltzmann's constant, T is temperature, V is the voltage across the *pn* junction, n_i is the intrinsic concentration, D is the diffusion coefficient , L is the diffusion length and N_a and N_d are the acceptor and donor doping concentrations. The subscripts e and h refer to electrons and holes respectively. If τ is the carrier lifetime (recombination time) then $L = \sqrt{D\tau}$. For the p^+n junction diode, the current I is primarily due to hole diffusion in the *n*-region and since $N_a >> N_d$,

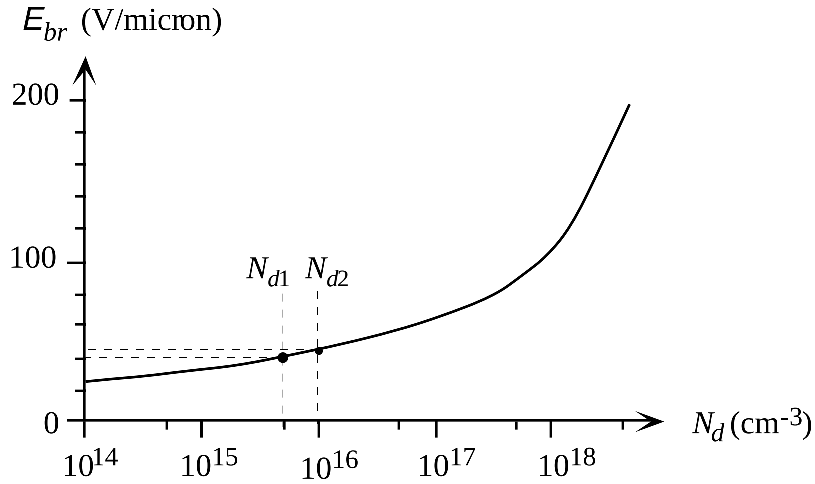
$$I \approx \frac{AeD_h n_i^2}{L_h N_d}\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \tag{2}$$

When the reverse bias is equal to V_{br}, the maximum field reaches the breakdown field $\mathcal{E}_{br}$. $\mathcal{E}_{br}$ is related to the dopant concentration N_d (because $d\mathcal{E}/dx = eN_d/\varepsilon_o\varepsilon_r$) and since $\mathcal{E} = -dV/dx$, $\mathcal{E}_{br}$ and V_{br} are related by,

$$V_{br} = \frac{\varepsilon \mathcal{E}_{br}^2}{2eN_d} \tag{3}$$

where $\varepsilon = \varepsilon_o\varepsilon_r$ is the permittivity, and ε_o and ε_r are the absolute and relative permittivities.

The critical field $\mathcal{E}_{br}$ for breakdown is not constant but depends on the dopant (donor in the case of p^+n) concentration N_d in the lightly doped region (*n*-side) . The $\mathcal{E}_{br}$ vs. N_d relationship for abrupt *pn* junction is shown in Figure 1.



The breakdown field, E_{br}, in the depletion layer for the onset of reverse breakdown vs. doping concentration, N_d, in the lightly doped region in a one-sided (p^+n or pn^+) abrupt *pn* junction. Avalanche and tunneling mechanisms are separated by the dashed line (data extracted from .M. Sze and G. Gibbons, Solid. State. Electronics, **9**, 831 (1966))

Figure 1

2. Design Specification

Design an abrupt Si pn^+ junction which has a reverse breakdown voltage of 80V and provides a current of 15 mA when the voltage across it is 0.6V. Assume that the minority carrier recombination time is given by

$$\tau = \frac{5\times10^{-7}}{1+2\times10^{-17}N_{\text{dopant}}} \qquad (4)$$

where N_{dopant} is the dopant concentration in cm^{-3}. Mention any assumptions made.

NOTE: Obviously this is a design question and involves assumptions. The final design must specify the approximate doping concentration and the device cross sectional area. Assume that the emitter current is due to minority carrier diffusion and not recombination in the depletion region.

3. Design Procedure

Since the reverse breakdown voltage V_{br} = 80 V is specified, the dopant concentration N_d is fixed by this specification. According to Eq. (3),

$$V_{br} = \frac{\varepsilon E_{br}^2}{2eN_d}$$

However, E_{br} also depends on N_d as in Figure 1 which means that we have to satisfy both Eq. (3) and also E_{br} vs. N_d in Figure 1. By trial and error we can substitute N_d and E_{br} from Figure 1 into Eq. (3) and calculate V_{br} until V_{br} is close to 80 V. The simplest way to locate approximately correct N_d, E_{br} choices is to find two values of N_d and hence E_{br} (Figure 1) that result in slightly higher and lower V_{br}. Then we use a power law interpolation.

Choose $N_d = N_{d1} = 1 \times 10^{16}$ cm^{-3}, $E_{br} = 45 \times 10^6$ V/m, and calculate from Eq. (3),

$$V_{br} = \frac{\varepsilon E_{br}^2}{2eN_d} = \frac{(8.85\times 11.9\times 10^{-12}\ \text{F m}^{-1})(45\times 10^6\ \text{V m}^{-1})^2}{2(1.6\times 10^{-19}\ \text{C})(1\times 10^{16}\times 10^6\ \text{m}^{-3})} = 66.6\ \text{V}$$

Choose $N_d = N_{d2} = 5 \times 10^{15}$ cm^{-3}, $E_{br} = 40 \times 10^6$ V/m, and calculate from Eq. (3), V_{br} = 105.2 V

From Eq. (3), since $E_{br} = f(N_d)$, we expect

$$V_{br} \propto \frac{E_{br}^2}{N_d} = \frac{f(N_d)}{N_d}$$

so we can try a power law interpolation,

$$N_d = CV_{br}^{-x} \tag{5}$$

We apply Eq. (5) at the two N_d and V_{br} values we found above as shown in the table below. We then find C and x and then calculate N_d at V_{br} = 80 V.

V_{br}	N_d (cm^{-3})	E_{br} (V/micron) from Figure 1	Eq. (5)	Comment
66.6	1×10^{16}	45	$(1 \times 10^{16}) = C(66.6)^{-x}$	Figure 1 and Eq. (3)
105.2	5×10^{15}	40	$(5 \times 10^{15}) = C(105)^{-x}$	Figure 1 and Eq. (3)
			$C = 5.8 \times 10^{18}$ $x = 1.5$	Find C and x in Eq. (5).
80	7.6×10^{15}			Calculated from Eq. (5)

From the above table, for V_{br} = 80 V we need a doping concentration, $N_d \approx 7.6 \times 10^{15}$ cm^{-3}. Since this is a pn^+ diode, N_d is the acceptor concentration N_a.

Equation (4) gives an electron recombination lifetime,

$$\tau = \frac{5\times 10^{-7}}{1+2\times 10^{-17}N_d} = \frac{5\times 10^{-7}}{1+2\times 10^{-17}(7.6\times 10^{15}\ \text{cm}^{-3})}$$

i.e. $\tau = 4.34 \times 10^{-7}$ s

The electron drift mobility μ_e at this doping (acceptor) concentration (7.6×10^{15} cm^{-3}) is approximately the same as that at room temperature, so that $\mu_e \approx 1350 \times 10^{-4}$ m^2 s^{-1} V^{-1}. The electron diffusion coefficient is

$$D_e = kT\mu_e/e = (0.0259\ \text{V})(1350 \times 10^{-4}\ \text{m}^2\ \text{s}^{-1}\ \text{V}^{-1}) = 0.0035\ \text{m}^2\ \text{s}^{-1}$$

The diffusion length is

$$L_e = \sqrt{D_e\tau} = \sqrt{(0.0035\ \text{m}^2\ \text{s}^{-1})(4.34\times 10^{-7}\ \text{s})} = 3.9 \times 10^{-5}\ \text{m}$$

Given that I = 15 mA when V = 0.6 V at room temperature, and the I-V relationship in Eq. (2),

$$I \approx \frac{AeD_e n_i^2}{L_e N_a}\exp\left(\frac{eV}{kT}\right)$$

substituting all the values leaves only A (device area) as undetermined:

i.e.,
$$15\times10^{-3}\text{ A} = \frac{A(1.6\times10^{-19}\text{ C})(0.0035\text{ m}^2\text{ s}^{-1})(1.45\times10^{10}\times10^{6}\text{ m}^{-3})^2}{(3.9\times10^{-5}\text{ m})(7.6\times10^{15}\times10^{6}\text{ m}^{-3})}\times\exp\left(\frac{0.6\text{ V}}{0.0259\text{ V}}\right)$$

Solving for A we find $A = 3.28 \times 10^{-6}$ m^2.

Making a circular device with a radius a, $\pi a^2 = A$, gives $a = 1.0 \times 10^{-3}$ m or about 1 mm as device radius.

The reverse saturation current I_{so} can be found from

$$I \approx I_{so}\exp\left(\frac{eV}{kT}\right)$$

or
$$15\times10^{-3}\text{ A} = I_{so}\exp\left(\frac{0.6\text{ V}}{0.0259\text{ V}}\right)$$

so that $I_{so} = 1.3 \times 10^{-12}$ A.

Device design is summarized in Table 1.

Table 1

Design of an abrupt Si pn^+ junction.

Device parameter	Value	Comment
I and V at 300 K	I = 15 mA when V = 0.6 V	Design specification
V_{br}	80 V	Design specification
N_a(p-side)	7.6×10^{15} cm^{-3}	Determined by breakdown voltage
A (device area)	3.28×10^{-6} m^2	Determined by I, V and N_d
N_{donor}(n^+-side)	>> 7.6×10^{15} cm^{-3}	Determined by specification of pn^+.
Device length	>> 39 μm	Determined by length of p-side >> L_e (long diode assumption)
I_{so}	1.3 pA	Reverse saturation current. Determined by $I_{so} = (AeD_e n_i^2)/(L_e N_a)$

4. Assumptions

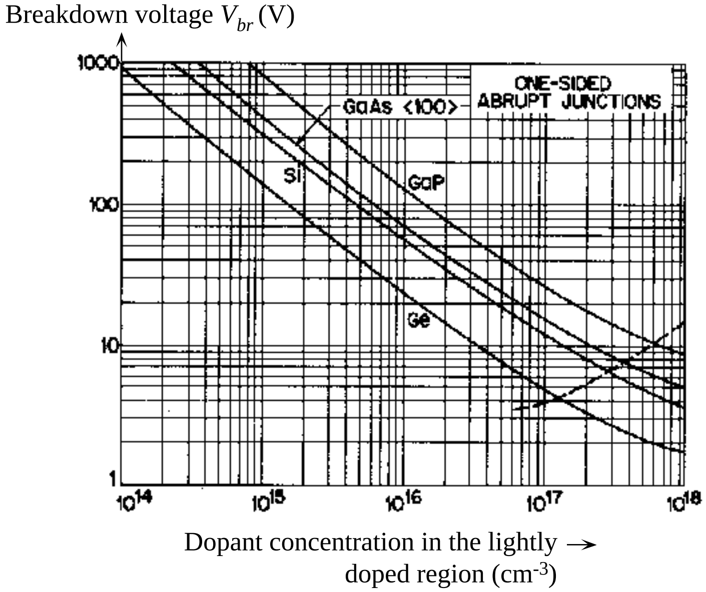
(1) Abrupt pn^+ junction.

(2) Current is determined by minority carrier diffusion in the neutral regions (Shockley equation applies).

(3) The diode is long: length of neutral regions are longer than minority carrier diffusion lengths.

(4) Resistance of the neutral regions is negligible so that the whole of the forward bias drops across the depletion region.

Note: Some authors provide the experimental relationship between V_{br} and N_d as shown in Figure 2. Given V_{br} = 80 V, we find, $N_d = 7.5 \times 10^{15}$ cm^{-3} very close to the value we found. Figure 2 is the result of combining Figure 1 and Eq. (3) and allows a one-step determination of N_d from V_{br}.



Avalanche breakdown voltage vs. dopant concentration in the lightly doped region of an abrupt *pn* junction. The dashed line indicates when tunneling breakdown begins to dominate as the dopant concentration increases further [Source: Figure 26 in *Physics of Semiconductor Devices, Second Edition*, S.M. Sze (John Wiley and Sons, New York, 1981) p.101]

Figure 2

NOTATION

A	cross-sectional area of device (πa^2 where a = radius)
D_e	electron diffusion coefficient ($m^2\ s^{-1}$) in the *p*-side. Note that $D/\mu = kT/e$
e	electronic charge (1.6×10^{-19} C)
E_{br}	breakdown field in the depletion region
I	current
J	current density ($A\ m^{-2}$)
k	Boltzmann constant ($k = 1.3807 \times 10^{-23}\ J\ K^{-1}$)
kT/e	0.0259 V at room temperature (~300 K)
L_h	hole diffusion length in the *n*-side (diffusion length, $L = \sqrt{D\tau}$, where D is the diffusion coefficient and τ is the recombination lifetime. Note that $D/\mu = kT/e$
N_a	acceptor concentration (m^{-3})
N_d	dopant (donor or acceptor) or donor concentration depending on context (m^{-3})
n_i	intrinsic concentration ($1.45 \times 10^{10}\ cm^{-3}$ for Si at room temperature)
T	temperature (K)
V	applied voltage; forward bias
V_{br}	breakdown voltage
V_r	reverse bias ($V = -V_r$)
ε	$\varepsilon_o\varepsilon_r$, permittivity; ε_o and ε_r are the absolute and relative permittivities
μ_e	drift mobility of electrons in the conduction band ($m^2\ V^{-1}\ s^{-1}$)
τ	minority carrier recombination lifetime (τ_e in the *p*-side of pn^+ diode)

USEFUL DEFINITIONS

Diffusion is the flow of particles of a given species from high to low concentration regions by virtue of their random motions. Diffusion flux Γ (number of particles diffusing through unit area per unit time) obeys Fick's first law, $\Gamma = -D(dn/dx)$ where D is the diffusion coefficient and dn/dx is the concentration gradient.

Long diode is a *pn* junction with neutral regions longer than the minority carrier diffusion lengths.

Minority carrier diffusion length (L) is the mean distance a minority carrier diffuses before recombination, $L = \sqrt{D\tau}$ where D is the diffusion coefficient and τ is the minority carrier lifetime.

Minority carriers are electrons in a *p*-type and holes in an *n*-type semiconductor.

***pn* junction** is a contact between a *p*-type and an *n*-type semiconductor. It has rectifying properties.

Recombination of an electron hole pair involves an electron in the conduction band (CB) falling in energy down into an empty state (hole) in the valence band (VB) to occupy it. The result is the annihilation of the EHP. The recombination process may be direct or indirect, depending on the semiconductor. In direct recombination (as in GaAs), the electron falls directly from the CB into a hole in the VB. In indirect recombination (as in Si), one of the carriers, for example the electron in the CB, is first captured by a recombination center such as a crystal defect or an impurity. The other carrier (a hole in the VB) then arrives at the recombination center and recombines with the captured carrier (electron). Thus, the electron first falls into a localized energy level (at the recombination site) in the bandgap. When a hole in the VB is in the neighborhood of the recombination center, the electron falls into this hole, resulting in an indirect recombination process.

Shockley diode equation relates the diode current to the diode voltage through $I = I_o[\exp(eV/kT) - 1]$. It is based on the injection and diffusion of injected minority carriers by the application of a forward bias.

"If current trends endure, future computers will consist of a single chip. No one will have the foggiest idea what is on it. Somewhere in the basement of Intel or its successor will be a huge computer file with chip's listing. The last electrical engineer will sit nearby, handcuffed to the disk drive in a scene out of Ben Hur. That engineer will be extremely well paid, and his or her every demand will be immediately satisfied. That engineer will be last keeper of the secret of the universe: *E* = *IR*."

Robert Lucky
(Spectrum, IEEE, May 1998 Issue, p.21)

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