OPTIMUM CHARGE-CARRIER LIFETIME IN PIN HIGH-VOLTAGE DIODES

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Introduction

The pin diode consists of three layers; p^+, i and n^+. The central layer i provides high reverse breakdown voltage. By forward biase holes from the layer p^+ and electrons from the layer n^+ enter into the central, high-resistivity layer, increasing the conductivity and decreasing the forward voltage drop. The carrier concentration in the central layer depends upon the lifetime of the carriers. At an optimum lifetime, to be calculated in this paper, the forward voltage of the pin diode is minimum. The theory of the pin diode has been discussed in detail in [1, 3, 4], although the concept of the optimum lifetime is not exposed. In the following a simplified, approximate method is presented for determining the optimum carrier lifetime.

Approximate solution

For the holes entering the central region through the junction $p^+ - i$, a high potential barrier exist at the junction $i - n^+$, therefore the holes stay and recombine in the region i. The same can be said for the electrons. Thus, the whole charge in the central region is:

$$Q_i = I_F \cdot \tau \tag{1}$$

where Q_i is the charge (electron *or* hole) and τ is the lifetime of the carriers. The lifetime of the holes and of the electrons is the same, because supposing quasi-neutrality in the layer i, the carrier concentrations are equal, too.

Thus, the average carrier concentration in the layer i is:

$$\bar{n} = \frac{Q_i}{qWA} = \frac{I_F \cdot \tau}{qWA} \tag{2}$$

where W is the width of the layer i, A is the cross-section of the diode. The actual carrier distribution, as shown in [1], differs from [2] assuming equal mobilities for both types of carrier, but the difference will be seen in the Appendix not to be great for optimum lifetimes or over. The whole forward voltage consists of three voltages:

a) the voltage drop across the junction $p^+ - i$,
b) the voltage drop in the layer i,
c) the voltage across the junction $i - n^+$.

The first and the third voltages can be calculated by the Boltzmann relation, thus assuming the carrier concentration to be constant throughout the layer i:

$$U_{p^+i} = U_T \ln \frac{p\left(-\frac{W}{2}\right)}{p_i} \approx U_T \ln \frac{\bar{p}}{n_i} = U_T \ln \frac{\bar{n}}{n_i} = U_T \ln \frac{n\left(+\frac{W}{2}\right)}{n_i} = U_{in^+} \tag{3}$$

Assuming constant carrier concentration in the layer i, there would be only drift currents. The more accurate calculation [1] takes also the diffusion currents into consideration, and it is shown that the diffusion currents compensate each other.

Calculating with an average mobility, the current is:

$$I_F = q \cdot A \cdot \mu \cdot E \cdot (n + p) = 2 \cdot q \cdot A \cdot \bar{\mu} \cdot E \cdot \bar{n} \tag{4}$$

and the field strength in the layer i from Eqs (2) and (4)

$$E_i = \frac{W}{2 \cdot \mu \cdot \tau} \tag{5}$$

The voltage drop in the layer i is:

$$U_i = E_i \cdot W = \frac{W^2}{2 \cdot \mu \cdot \tau} \tag{6}$$

It should be emphasized that in the above equation U_i doesn't depend upon I_F. Increasing the current increases the carrier concentration according to Eq (2), and decreases the resistivity of the layer i.

The total forward voltage from Eqs (2), (3) and (6) is:

$$U_F = U_{p^+i} + U_i + U_{in^+} = 2 \cdot U_T \cdot \ln\left(\frac{I_F \cdot \tau}{q \cdot A \cdot W \cdot n_i}\right) + \frac{W^2}{2 \cdot \mu \cdot \tau} \tag{7}$$

U_F tends to infinity if τ tends to zero or infinity, therefore, there should be a minimum for U_F. Deriving U_F yields

$$\frac{dU_F}{d\tau} = -\frac{W^2}{2 \cdot \mu \cdot \tau^2} + \frac{2 \cdot U_T}{\tau} = 0$$

thus the optimum lifetime is:

$$\tau_{\text{opt}} = \frac{W^2}{4 \cdot \mu \cdot U_T} = \left(\frac{W}{2}\right)^2 \cdot \frac{1}{D} \tag{8}$$

where D is the ambipolar diffusion constant [1]:

$$D = \frac{2 \cdot D_n \cdot D_p}{D_n + D_p}$$

Thus a very simple expression is obtained for the optimum lifetime. It is seen in Eq. (8) that the optimum lifetime is independent of the forward current and is determined only by the width of the layer i, making possible the optimum construction of the pin diode.

The minimum value of the voltage from (7) and (8) is:

$$U_{F\min} = 2 \cdot U_T \cdot \left(\ln \frac{I_F \cdot W}{4 \cdot q \cdot A \cdot D \cdot n_i} + 1\right) \tag{9}$$

By increasing the lifetime beyond the optimum, the forward voltage increases slightly. However, by decreasing the lifetime below the optimum the forward voltage rises sharply, therefore, the production of the pin diodes should consider τ_{opt} as lower limit for the carrier lifetime. The exact value of τ_{opt} has been determined in [5], and it is very close to (8).

The calculated optimum lifetime can also be used for silicon controlled rectifiers. At high injection levels the central regions (the two central layers of the p^+npn^+ structure) behave like an intrinsic layer, because the injected carrier densities are much higher than the doping concentrations in the forward direction and the carrier distribution is similar to the distribution in the pin diode [2].

In the Appendix the actual carrier distribution in the layer i is seen to slightly differ from the approximate one.

Appendix

Assuming equal mobilities for electrons and holes, the carrier distribution is, according to [1]:

$$n(x) = p(x) = \frac{L}{2 \cdot q \cdot \mu \cdot U_T} \cdot i_F \cdot \frac{Ch\left(\frac{x}{L}\right)}{\text{sh}\left(\frac{W}{2 \cdot L}\right)} \tag{A.1}$$

where L is the ambipolar diffusion length. For $\tau = \tau_{\text{opt}}$, using Eq. (8)

$$L = \sqrt{D\tau} = \sqrt{D\tau_{\text{opt}}} = \frac{W}{2} \tag{A 2}$$

and the maximum variation of the concentration

$$\frac{n\left(-\frac{W}{2}\right)}{n(O)} = \frac{\text{ch}\left(\frac{W}{2 \cdot L}\right)}{\text{ch}\,(O)} = \text{ch}\,(1) = 1.54 \tag{A 3}$$

Thus the maximum deviation from the mean value is about $\pm 25\%$.

Summary

The forward voltage of the pin diode has been determined by approximate calculation. An optimum charge-carrier lifetime is presented, where the forward voltage is minimum. The deviation from the exact calculation is shown to be insignificant.

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