Losses in Power Diodes

J. Garcia, DIEECS, University of Oviedo, Spain

I. Introduction

The following is a basic introduction to obtaining the static characteristics of power semiconductors. Then, the main operating states in power applications will be identified. After that, the dynamic characteristics (switching waveforms) will be discussed.

Ultimately, the switching and conduction losses in semiconductors will be analyzed.

Finally, a summary of soft-switching techniques will be discussed, including ZVS-ZCS techniques, resonant converters and snubbers.

II. Switching Characteristics of Power Diodes

In power converters, the power semiconductors are usually operated in switching modes. Therefore, the switching transients are critical to understand the capabilities of the devices under consideration. The power dissipation largely depends on the device temperature. Also, the dynamic performance is better understood if the junction capacitance is considered.

The Shockley equation is valid in steady state. It can be rewritten as:

$$0 = i - \frac{Q_0}{\tau_L}\left(e^{\frac{v}{n \cdot V_T}} - 1\right) = i - \frac{q(t)}{\tau_L} \quad (1)$$

In this expression, valid for equilibrium, the following identity is assumed:

$$q(t) = Q_0\left(e^{\frac{v}{n \cdot V_T}} - 1\right) \quad (2)$$

where the magnitude q(t) is the total charge due the minority carriers stored in the lattice, and it is related with the *slopes* of the concentration of minority carriers at the N and P edges of the depletion region. The second term of the right side of the equation (1) is related to the rate of recombinations of minority carries in the diode.

The key aspect is to consider what happens if equilibrium is broken. The variation of the stored charge, q(t), might take place due two different mechanisms.

As mentioned before, the forward current is related to the charge flow due the minority carriers in both junction sides. Therefore, a change in the current implies a variation on the minority charge flow. But this flow is also directly related to the total stored charge.

On the other hand, if the rate of recombinations of minority carriers changes, the stored charge also varies. But the rate of recombinations depends on the amount of charge itself.

Therefore, the following dynamic equation can be established:

$$\frac{dq(t)}{dt} = i - \frac{q(t)}{\tau_L} \quad (3)$$

This equation is critical to understand diode turn-on and turn-off processes.

a) Diode turn-off

Again, the current depends on the charge flow due the minority carriers. This is true in particular for the cross-section of the depletion region close the N and P regions. It is critical to consider that the variation in the charge flow (current), implies a variation in the concentration of minority carriers in the edges of the depletion region. In particular, *the current is bond to the slope of the minority carrier spatial distribution in the edges of the depletion region* (i.e. variation of the minority carriers concentration ad these locations). This slope implies the variation of concentration, that is the prime mover of the minority chargers, given that they move by diffusion causes.

Assuming a net current flowing and an equilibrium situation, then dq(t)/dt=0, and an existing stored charge due minority carriers is present, as given by (2).

In order to turn the diode off, a reverse voltage is provided to the device. This reverse voltage removes minority carriers from the diode. But the process is that the majority carriers in region N, i.e. (-), flow towards the cathode, and drain (-) from the P region as well, where they are minority carriers. Thus the concentration of minority chargers evolves as in the figure 8, in the t_1-t_8 sequence. Given that the slope of the concentration in this edge is related to the current flowing by the diode, this current experiments a sign reversal, while the total stored charge decreases. When the concentration at the edge of the depletion region is equal to zero, the depletion region starts to enlarge, as the stored charge further decreases, the current is still negative but also decreases, the voltage starts to increase and the junction capacitance starts also to change.

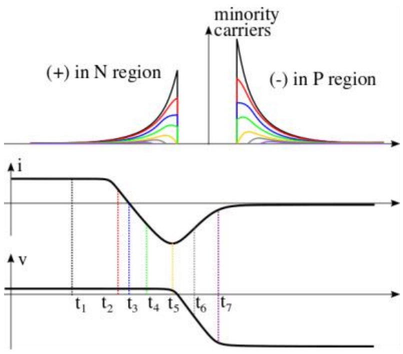

Figure 1 Relationship between concentration of minority carriers and turn-off waveforms

This issue is the reverse recovery phenomenon. From fig. 9, it can be seen how the power losses at the diode itself, associated to this phenomenon, are not very significant, and can be generally neglected.

The expression that provides these turn off losses of the diode due the reverse recovery are given in [2]:

$$P_{D_{Turn\,off\,RR}} = \frac{1}{6} I_{RR} \cdot V_R \cdot t_b \cdot f_{SW} \quad (4)$$

However, this phenomenon implies a major concern when the diode is connected to a power transistor (e.g. boost, buck converters), but also in every power topology based in half bridge structure. In this case, though, the value of the switching times, t_a, t_b, and t_{rr}, can only be calculated from the gate characteristics of the transistor and the exeternal circuit connected to the diode. A detailed expression for the calculation of this phenomenon will be discussed **in the document related to Power MOSFETs**.

It also must be notice that this phenomenon affects minority carrier diodes, (PN, PIN, etc.), but *not majority carrier rectifiers, such as the Schottky diode*.

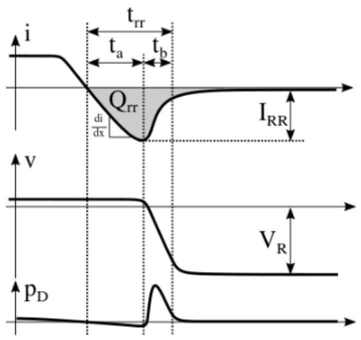

Figure 2 Detailed turn-off characteristic, including the reverse recovery phenomenon

b) Junction capacitance

From the semiconductor structure, clearly a parasitic capacitance appears in the limits of the depletion region. Given the usual formula of a capacitance,

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \quad (5)$$

that depends on the distance between plates, and given that the junction width changes with the diode voltage, this capacitance is in fact a function of the diode voltage.

The charge stored in the capacitance of the diode is lost in the turn on process, and therefore these losses must also be considered [1]:

$$P_{D_{Turn\,off\,C}} = \frac{1}{2} C_R \cdot V_R^2 \cdot f_{SW} \quad (6)$$

c) Diode Turn-on and PIN diodes

The diode turn-on is much simpler, since no stored charge is initially in the device. The injection of minority chargers in the lattice is usually very fast. The waveforms at turn on can be seen in Figure 10.

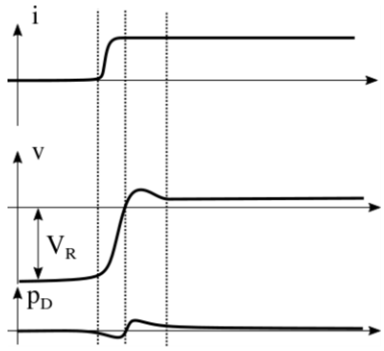

Figure 3 Structure of a PIN diode.

There are not losses due the charging of the capacitance. In fact, in some cases this charging can be computed as recovered energy to the system, yielding to apparently negative losses in the turn on sequence [1].

In PIN diodes, relatively large initial resistive behavior is observed, until conductivity modulation takes place and this resistive value decreases. The conductivity modulation consists on that initially, the depletion region has no carriers, and therefore the intrinsic region presents a high resistivity. However, majority carriers are injected during turn on, that decrease this resistance.

PIN diodes are interesting since the breakdown voltage (reverse voltage) can be made much higher than in standard PN diodes. Figure 10 schematizes a PIN diode.

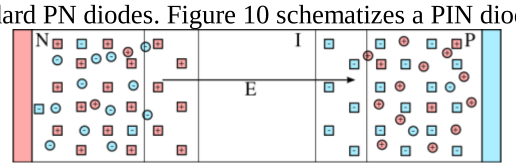

Figure 4 Structure of a PIN diode.

Still the turn on losses in the diode can be generally neglected.

d) Thermal behavior

The characteristics of the material and the Shockley equation are function of the temperature. But the temperature is also a parameter that changes with the power dissipated by the diode. The Thermal equation can be stated:

$$P_D = \frac{T_{junction} - T_{ambient}}{\theta_{Thermal}} \quad (7)$$

where T is the temperature (in ºC or K), and θ is the thermal resistance, in ºC/W.

The variation of this thermal resistance, as well as the variation of the main parameters of the diode with temperature are given at the diode datasheets.

III. Diode Losses

Diode losses can be divided in to conduction losses and switching losses:

$$P_D = P_{D_{cond}} + P_{D_{switch}} \quad (8)$$

a) Conduction losses

The typical forward voltage linear characteristic will be used, as shown in figure 7:

$$v(\mathrm{i}) = V_F + \mathrm{i} \cdot R_d \quad (9)$$

The parameters of the threshold voltage, V_F, and dynamic resistance, R_d, can be obtained from the datasheets. As mentioned, these parameters depend on the temperature.

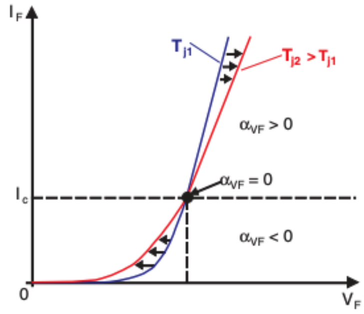

Figure 5 Dependence of junction characteristic with temperature [5]

In order to calculate the forward voltage, V_F, and dynamic resistance, R_d from the V-I characteristics, two points at the reference temperature, T_{JREF} will be selected (if this temperature is not depicted, a linear interpolation will be carried out). These two points will be chosen well above the knee of the curve, points $A(v_A,i_A)$ and $B(v_B,i_B)$. For reference figure 12 considers a logarithmic representation of the V-I characteristic.

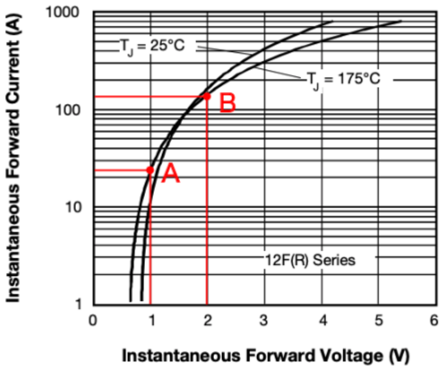

Figure 6 Real V-I characteristic ofa power diode [4].

From these two parameters, the final values can be calculated easily:

$$R_d = \frac{v_B - v_A}{i_B - i_A} \quad (10)$$

$$V_F = v_A - i_A \cdot R_d \quad (11)$$

With these parameters, then

$$P_{D_{cond}} = \int_{t=0}^{t=T} (i(t) \cdot v(t)) \cdot dt \quad (12)$$

Finally, this expression can be turned into:

$$P_{D_{cond}} = I_{RMS}^2 \cdot R_d + V_F \cdot I_{AVG} \quad (13)$$

b) Switching losses

As mentioned before, the swithing losses can be expressed by:

$$P_{D_{switch}} = P_{D_{Turn\,off}} = P_{D_{Turn\,off\,C}} + P_{D_{Turn\,off\,RR}} \quad (14)$$

and therefore

$$P_{D_{switch}} = \frac{1}{2} C_R \cdot V_R^2 \cdot f_{SW} + \frac{1}{6} I_{RR} \cdot V_R \cdot t_b \cdot f_{SW} \quad (15)$$

Thus, the total losses in the diode can be calculated as:

$$P_D = I_{RMS}^2 \cdot R_d + V_F \cdot I_{AVG} + $$
$$+ \frac{1}{2} C_R \cdot V_R^2 \cdot f_{SW} + \frac{1}{6} I_{RR} \cdot V_R \cdot t_b \cdot f_{SW} \quad (16)$$

IV. Conclusions

The diode losses depend on the V-I characteristics of the diode and on the dynamic parasitic elements. Among these, the switching times depend on the external circuit, e.g. on the associated controlled switch timing, mainly given by the driver. Also the current and voltage waveforms affect.

Once estimated, these parameters can be introduced in equation (16), and a first guess of the dissipated power, P_D, can be estimated. This value must be introduced in equation (7), and the value of the junction temperature can be extracted. A iterative process starts, until all the values are consistent.

However, this will affect the rest of the circuit as well, and ultimately all the design must be consistent at full system level.

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