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Simulation of storage time versus reverse bias current for p^+n and pin diodes

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Abstract

In this study, the reverse-recovery behaviors of pin and p^+n diodes were simulated as a function of the reverse current and carrier lifetime. For this purpose, a 1-D simulation program was written to solve the semiconductor equations. MatLab partial differential equation solver was used. The reverse recovery response of pin and p^+n diodes was obtained for various values of a resistor in series and of carrier lifetime. The transient response for voltage and current was determined.

Key Words: *Reverse recovery, pin diode, semiconductor devices, semiconductor devices simulation*

1. Introduction

The pin diode is an important semiconductor structure in power electronics. Many power switches have a region which can be modeled as pin diode. The reverse bias response of the pin structure may have crucial role in the operation of these switches. It may cause excessive voltages and currents in the components in a power circuit. The diode models utilized by SPICE are basically based on charge-control concept under low-injection conditions. Such models are not proper for pin power structures. This has led to many models for the power diode [1–9].

In the model provided by Gosbell [1], the recombination at the terminals is neglected, and the reverse recovery time is calculated by the convolution integral. For the carrier distribution in the base of the power diode, Strollo [2] solves the ambipolar diffusion equation

$$\frac{\partial^2 p}{\partial x^2} = \frac{p}{L_a^2} + \frac{1}{D_a}\frac{\partial p}{\partial t}, \qquad (1)$$

where D_a is the ambipolar diffusion coefficient and L_a is the ambipolar diffusion length.

Strollo suggested a generalization for the model by Gosbell [1] and included the emitter recombination effect on the reverse recovery time. This led to a model that is easily used with SPICE simulator. Later, in addition to the reverse-recovery response, Maxim [3] studied the forward-recovery response and temperature effects on pin diodes that can be a separate power-electronic component or a region in a semiconductor controlled switch such as VDMOSFET or IGBT.

In the present study, a 1-D simulator is developed to solve the semiconductor equations via MatLab partial differential equation solver. With the simulator, p^+n and pin reverse-recovery responses were studied. The simulation was carried out for various carrier lifetime values for the drift region, and the transient response voltage and current values were obtained. The results are presented in graphical forms.

2. Simulation program

The fundamental semiconductor current density equations for electrons and holes are as follows [10]:

$$\vec{J}_n = e\mu_n n\vec{E} + eD_n \nabla n \tag{2}$$

$$\vec{J}_p = e\mu_p p\vec{E} - eD_p \nabla p \tag{3}$$

The continuity equations are

$$\frac{\partial n}{\partial t} = \frac{1}{e} div\vec{J}_n + U_n \tag{4}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{e} div\vec{J}_p + U_p, \tag{5}$$

and the Poisson equation is

$$GradV = -\frac{e}{\varepsilon}\left(p - n + N_D^+ - N_A^-\right). \tag{6}$$

Here, U_n and U_p represent net generation rates and can be expressed as the difference between generation and recombination rates:

$$U_n = g_n - R_n, \tag{7}$$

$$U_p = g_p - R_p. \tag{8}$$

R_n and R_p represent the Shockley-Read-Hall recombination rates and are assumed to be equal:

$$R_n = R_p = \frac{np - n_i^2}{\tau_n\left(p + n_i\right) + \tau_p\left(n + n_i\right)}, \tag{9}$$

where τ_n and τ_n are minority carrier lifetimes. For simplicity, complete ionization of acceptors and donors is assumed; hence, $N_D^+ = N_D$ and $N_A^- = N_A$.

3. Reverse recovery process

The circuit in Figure 1 is used to study the transient behavior of the diode when it is switched from forward bias (position a) to reverse bias (position b). The resistor in the circuit limits the initial reverse current.

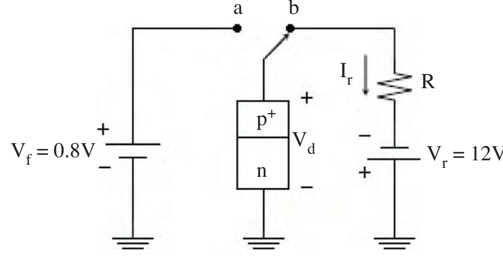

Figure 1. Circuit for the reverse-recovery analysis.

After switching, a voltage equation for the circuit may be written

$$V_d - V_R + V_r = 0. \tag{10}$$

Here, $V_R = I_r R$; and the reverse current, I_r, can be obtained as

$$I_r = (V_r + V_d)/R. \tag{11}$$

Right after switching, the diode voltage will be about the same as the forward bias voltage, and it will be much smaller than the source voltage in the circuit. Thus, the initial reverse current can be approximated as

$$V_d << V_r \Rightarrow I_r \cong V_r/R \tag{12}$$

The reverse current would be limited by the value given by equation (12). The junction capacitance of the diode does not allow sudden changes in the voltage, and the gradient of the carrier densities remain constant because the reverse current is limited and kept constant right after switching.

The reverse current I_r is almost constant for the time interval $0^+ \leq t \leq t_s$. Here, t_s is storage time. This length of time is required for the minority carrier density to fall back to its thermal equilibrium value. After the storage time, the voltage across the junction starts to decrease faster. The reverse current, too, decreases to its steady state value once the excess carriers are removed from the diode. The current transient response for the reverse recovery period is shown in Figure 2.

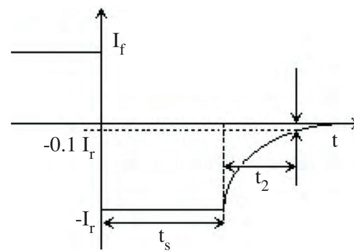

Figure 2. The reverse-recovery transient response of the current in a diode.

The storage time t_s may be found by solving the time-dependent continuity equation. For a one-sided p^+n junction, the storage time is found through the expression

$$erf\sqrt{\frac{t_s}{\tau_{po}}} = \frac{I_f}{I_f + I_r}. \tag{13}$$

An approximate solution [10] for the storage time would be related to the minority excess carrier lifetime τ_{p0}:

$$t_s \cong \tau_{p0} \ln\left(1 + \frac{I_f}{I_r}\right). \tag{14}$$

After the storage time, the excess carriers are completely removed from the quasi-neutral regions, and the depletion region expands to reach its steady-state boundaries. The total turn-off time is the sum of the storage time t_s and the decay time t_2 [11], as shown in Figure 2. The minimum switching time for a diode depends not only on the minority excess carrier lifetime, but also the initial reverse current. Hence, the designers should provide a path for the initial reverse current pulse of the diode to have the diode switch faster.

4. A flow-chart for the reverse recovery simulation program

In the circuit in Figure 1, the switch is moved from position (a) to position (b) at $t = 0$. After time interval Δt, the diode voltage falls to V_{D1} from V_f =0.8 V. The reverse current in the circuit is

$$I_{r1} = (V_r + V_{D1})/R. \tag{15}$$

The initial reverse current at t=0$^+$ is taken as

$$I_{r0} = (V_r + V_f)/R. \tag{16}$$

The reverse current is assumed to decrease from I_{r0} to I_{r1} linearly over time interval Δt, and the average current over this interval is taken as

$$I_{Rave} = (I_{r0} + I_{r1})/2. \tag{17}$$

After the switching, the minority carrier densities would change. At the end of the time period Δt, the carrier densities would drop as shown in Figure 3. Here, $n_0(x)$ and $p_0(x)$ represent the carrier densities at $t = t_0$ =0$^+$ while $n_1(x)$ and $p_1(x)$ represent the densities at $t = t_1 = t_0 + \Delta t$.

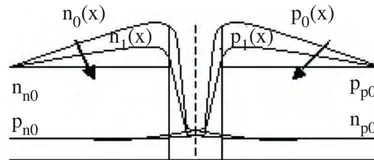

Figure 3. The carrier profiles after the switching. The arrows indicate the progress in time.

The change in the amount of charge ΔQ over the interval Δt is related to the average current,

$$I_{Qave} = \Delta Q/\Delta t. \tag{18}$$

Since the diode and the resistor are in series,

$$I_{Rave} = I_{Qave}. \tag{19}$$

Thus, Δt and I_{Rave} time-current pairs are determined. The entire reverse-recovery process is analyzed with such time-current pairs [12]. A program was written for this, and its flow-chart is given in Figure 4.

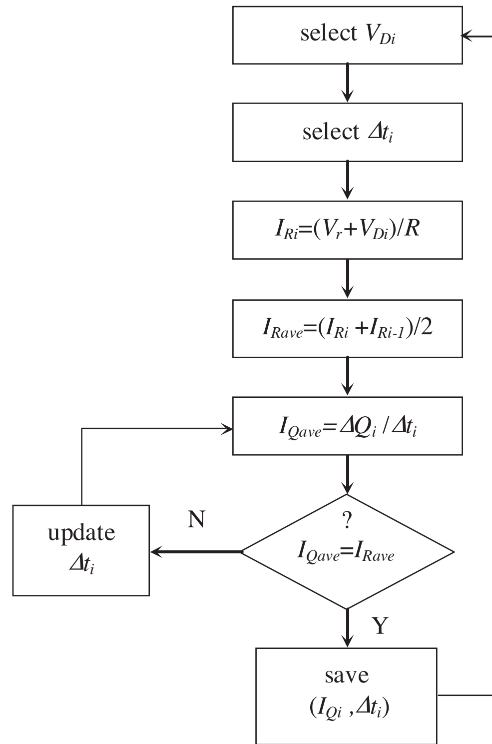

Figure 4. The flow-chart for the program to determine current-time pairs.

5. Simulation results

The p^+n and pin structures that are used in the simulation are given in Figure 5. The junction area for both structures is assumed to be 0.0604 cm^2, which results in a forward current of 1.209 A for the p^+n structure, and 3.523 A for the pin structure with a 0.8 V forward bias.

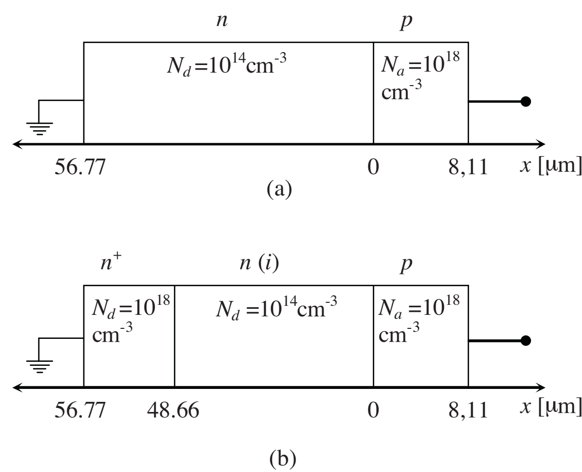

Figure 5. Diode geometries for simulation: a) p^+n diode, b) pin diode.

The steady-state DC voltage-current characteristics of p^+n and pin diodes that have the structures given in Figure 5 are shown in Figure 6.

The reverse-recovery transient curves of the p^+n diode are given in Figure 7 and Figure 8 for six different values of R. The excess minority carrier lifetime was assumed to be 0.5 μs for the simulation.

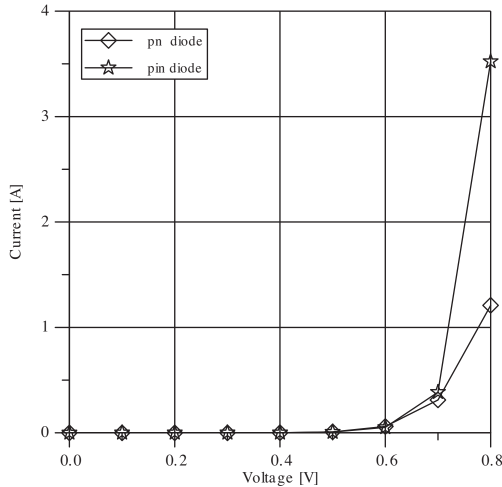

Figure 6. I-V characteristics for p^+n and pin diodes.

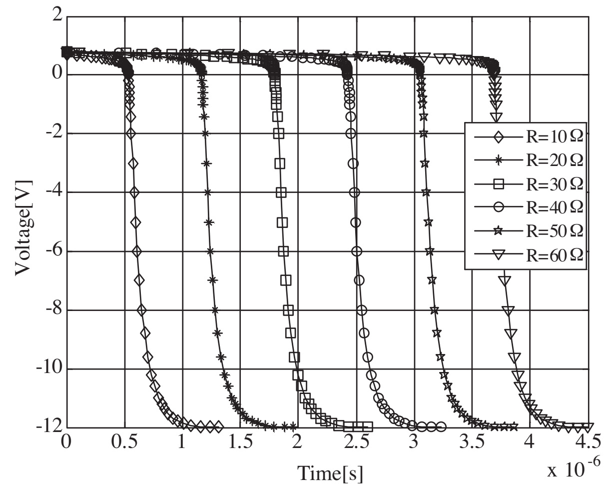

Figure 7. The reverse-recovery voltage transient curves of the p^+n diode for 0.5 μs lifetime after a forward current of 1.209 A at 0.8 V.

The reverse-recovery current transient curves of the p^+n diode for 1.0 μs and 1.5 μs excess minority carrier lifetime are given in Figure 9.

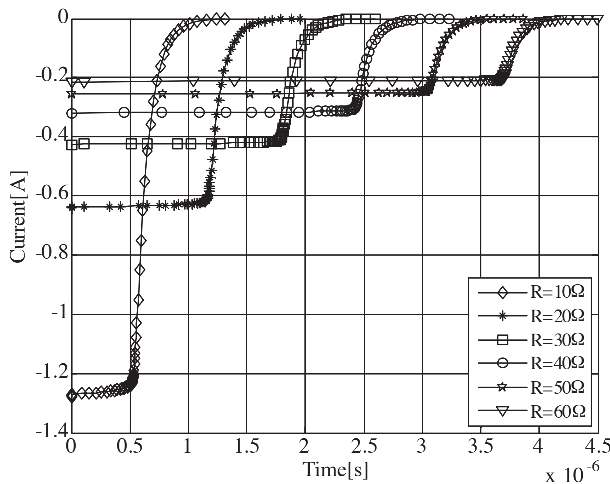

Figure 8. The reverse-recovery current transient curves of the p^+n diode for 0.5 μs lifetime after a forward current of 1.209 A.

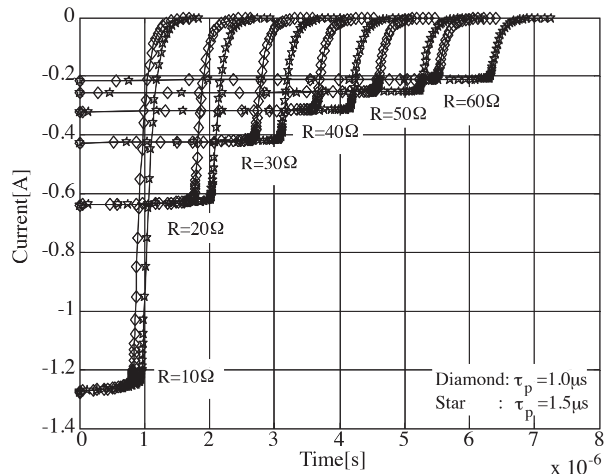

Figure 9. The reverse-recovery current transient curves of the p^+n diode for 1.0 μs and 1.5 μs ifetime after a forward current of 1.209 A.

The reverse-recovery transient curves of the pin diode are given in Figure 10 and Figure 11 for six different values of R. The excess minority carrier lifetime was assumed to be 0.5 μs for the simulation. Figure 12 has

the current transient curves of the pin diode for 1.0 μs and 1.5 μs excess minority carrier lifetime.

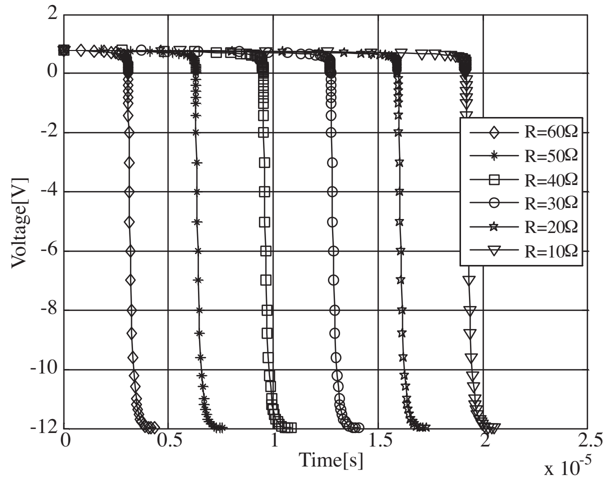

Figure 10. The reverse-recovery voltage transient curves of the pin diode for 0.5 μs lifetime after a forward current of 3.523 A at 0.8 V.

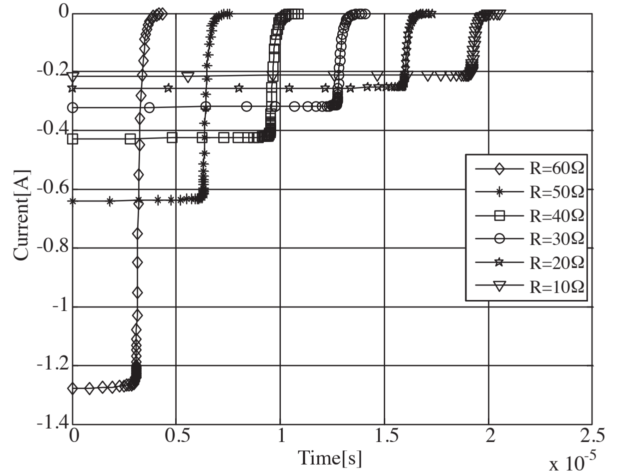

Figure 11. The reverse-recovery current transient curves of the pin diode for 0.5 μs lifetime after a forward current of 3.523 A.

As defined in Figure 2, the storage time for the p$^+$n diode can be found from the curves given in Figure 7 and Figure 8 for a specific value of initial reverse current. The value of the initial reverse current is set by the value of R in the circuit. The storage time depends on the excess charge in the structure, and the excess charge depends on the forward current of the device. Hence, rather than finding the storage time as a function of reverse current only, the ratio of the initial reverse current to the forward current is taken as the independent variable. The storage time of the p$^+$n structure for various minority carrier lifetime values is plotted against I_r/I_f in Figure 13.

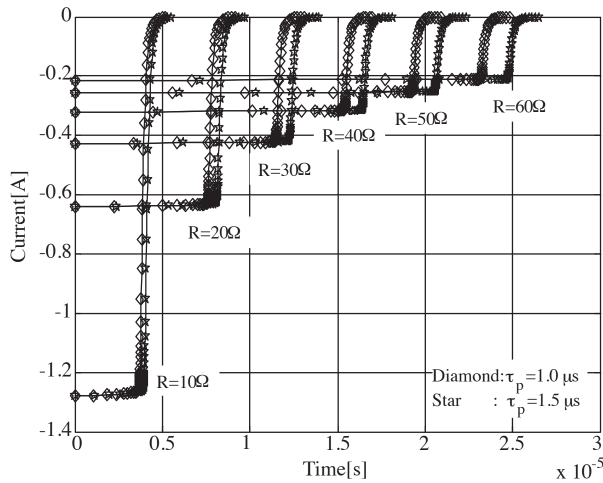

Figure 12. The reverse-recovery current transient curves of the pin diode for 1.0 μs and 1.5 μs lifetime after a forward current of 3.523 A.

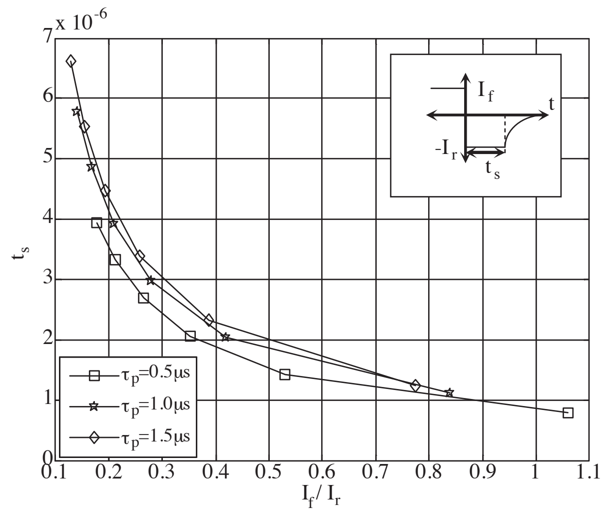

Figure 13. The storage-time versus I_r/I_f for the p$^+$n diode for three values of minority carrier lifetime.

The analysis that had been carried out for p^+n structure was repeated for the pin structure. The forward current is calculated for the given minority excess carrier lifetime. The storage time of the pin structure for various minority carrier lifetime values is plotted against I_r/I_f in Figure 14. The storage time values for both devices are plotted together in Figure 15.

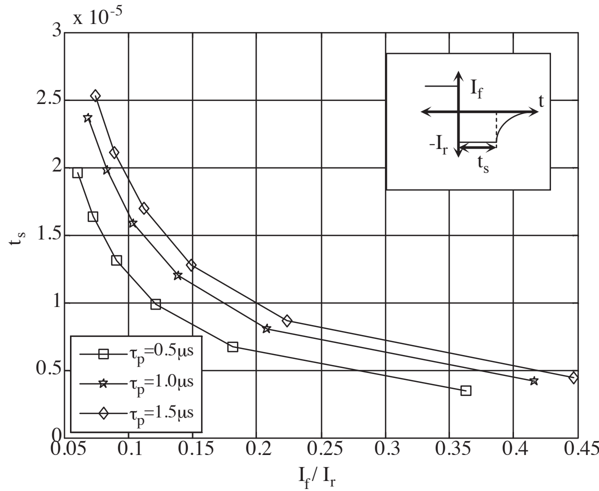

Figure 14. The storage-time versus I_r/I_f for the pin diode for three values of minority carrier lifetime.

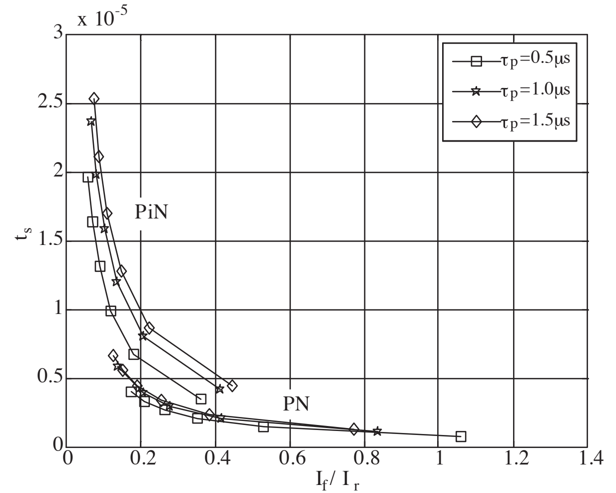

Figure 15. The storage-time versus I_r/I_f for the p^+n and pin diodes for three values of minority carrier lifetime.

The simulation results are compared with the analytical expression for the p^+n diode. Equation (7) was used to estimate of analytical storage time. The comparison is given in Figure 16. The simulation results are higher than the values suggested by the analytical expression.

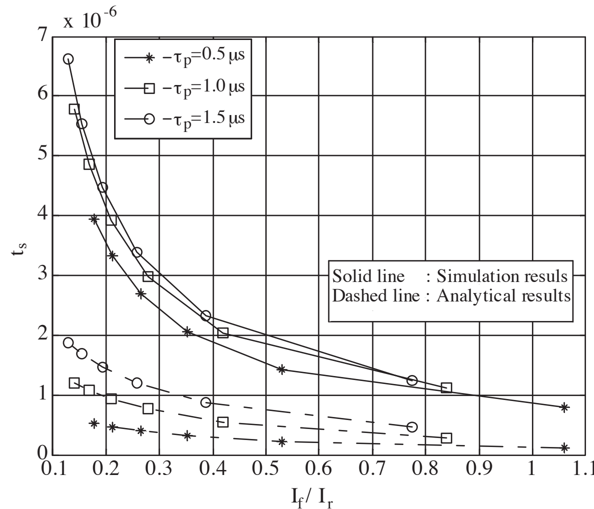

Figure 16. The storage-time versus I_r/I_f for the p^+n diode for three values of minority carrier lifetime: simulation and analytical results.

6. Conclusion

The reverse-recovery storage time of a p^+n and a pin structure was studied as a function of initial reverse current. The initial reverse current was modified by the selection of the resistor R in the circuit of Figure 1. The transient responses were obtained via the simulation of the circuit for six different values of R and three different values of excess minority carrier lifetime. MatLab partial differential equation solver was called during the simulation. The results were presented in Figures 7–14. From the current transient curves, the storage time was determined for both devices.

The storage time is plotted for varying I_r/I_f ratio and for three minority carrier lifetime values for both devices in Figure 15. It is clear from the figures that the reverse-recovery storage time decreases as the I_r/I_f ratio increases.

Under forward bias, carriers are injected across the junction. The injected carriers form the excess charge in the quasi-neutral regions. When the diode is reverse biased, this charge changes direction and continues to flow. Before the diode reaches the "blocking" stage, the excess charge in the device must be removed. There are two parallel mechanisms for this. First one is the initial reverse current. The larger the initial reverse current, the faster the removal process, and the shorter the storage time. The second mechanism is the recombination process. The larger the excess carrier lifetime, the longer it takes to remove the excess charge and the larger the storage time.

A contrast of storage times for the p^+n and pin structure reveals that the storage time for the pin diode is larger than that of the p^+n diode for the same minority carrier lifetime and I_r/I_f ratio. Figure 15 reveals that the storage time for the pin diode is more sensitive to the minority carrier life time than that of the p^+n diode is. This is due to the larger amount of excess charge stored in the base of the pin diode.

The simulation results for the p^+n junction differ from the numbers predicted by the analytical expression as displayed in Figure 16. The difference is could be due to the approximate nature of the expression given in equation 14. Although the numbers are different, the shape of the curve is the same for both analytical predictions and simulation results.

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