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New analytic 1D *pn* junction diode photocurrent solutions following ionizing radiation and including time-dependent changes in the carrier lifetime from a non-concurrent neutron pulse[1]

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Abstract

A new transient analytic excess carrier density and photocurrent solution for an irradiated 1D abrupt *pn* junction diode taking into account a time-dependent change in carrier lifetime due to neutron irradiation is presented with examples.

1 Summary

Numerical device simulators, capable of simulating non-linear and multi-dimensional transient drift/diffusion carrier movement and the resulting photocurrents are commonly used in the electronics community(e.g. [1]). While such simulators, which discretize the set of equations on a spatial mesh, can provide detailed solutions, they typically require hours of compute time for a single semiconductor device. Device simulators are sometimes incorporated into circuit simulators, such as SPICE [2] or Xyce [3], but are computationally prohibitive beyond application to a handful of transistors. Qualifying circuits in the presence of ionizing radiation requires SPICE simulations consisting of thousands of devices (or more). As such, the development of scalable compact models is crucial.

The transport behavior of excess carriers in semiconductors is described by the equations of current and continuity for electrons and holes, as well as Poisson's equation, which relates the electric field and net charge density. For each carrier, the current equation may be substituted into the continuity equation, resulting in three equations describing carrier transport (pp. 320-327, [4]). The three resulting equations are not amenable to exact analytic mathematical analysis. The electrical neutrality or charge balance approximation suggested by Van Roosbroeck [5] is used to combine the electron and hole current-continuity equations into the single ambipolar diffusion equation (ADE) (pp. 327-328 [4]).

Analytic solutions to the ADE for the photocurrent response to radiation for components of devices may be easily incorporated into circuit codes, although perhaps at the expense of some accuracy in calculation. Analytic mathematical models([6],[7],[8]) have been developed over the past four decades that predict transient radiation or light-induced photocurrents due to excess carrier generation in 1D *pn* junction diodes. These models all assume constant material properties within each doped region.

Neutron damage to semiconductor devices have been studied by a number of authors ([9], [10]). Neutrons collide and displace lattice atoms in semiconductors creating Frenkel defects. which may combine with dopant and impurity atoms to form stable defects, which as recombination centers decrease carrier lifetime. The temporal response of the carrier lifetime to a neutron burst has been characterized as an abrupt decrease followed by annealing periods([10], [9]).

Figure 1 shows a reverse biased *pn* diode under light or ionizing radiation. We assume ohmic contacts at the device ends. The local coordinates are taken for convenience in the mathematical analysis. The current for the entire device consists of the sum of the depletion zone current along with the two minority carrier diffusion currents from the undepleted regions [6]. This study generalizes an existing photocurrent solution [8] for the particular case where there is a time-dependent change in the carrier lifetime during or immediately after irradiation. Such behavior might be expected for a neutron pulse that is not coincident with the device irradiation.

In Cartesian coordinates under the assumption of charge neutrality and a time-dependent carrier lifetime, the one-dimensional ADE may be written ([5],[4]),

$$u_t = D_a u_{xx} - \mu_a E u_x - \frac{1}{\tau_a(t)} u + g(x,t) \qquad , \qquad 0 \le x \le L \qquad , \qquad t > 0 \tag{1}$$

where $u(x,t)$ is the excess carrier density, $g(x,t)$ is the excess carrier generation rate (in excess of the thermal carrier generation rate) due to irradiation, and L is the length of the undepleted n-type region, labeled as X_1 in Figure

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1. The equations for the ambipolar coefficients, D_a and μ_a and $\tau_a(t)$ are given on page 328 of McKelvey [4]. E is the electric field, composed of an internal field due to internal charged carriers and an applied field due to an applied potential. The ambipolar carrier lifetime $\tau_a(t)$ is assumed a spatially uniform function of time throughout the device. Inherent in the derivation of the ambipolar diffusion equation, when the lifetime is assumed a function of time, is the assumption that both the minority and majority carrier lifetimes are affected equally with respect to time. Specifically, equation (10.2-29) of reference [4], becomes $\tau_a(t) = \frac{p_0+u}{\tau_p(t)} - \frac{p_0}{\tau_{p0}} = \frac{n_0+u}{\tau_n(t)} - \frac{n_0}{\tau_{n_0}}$, where τ_{p_0} and τ_{n_0} are the initial average hole and electron carrier lifetimes respectively, under pre-irradiation thermal equilibrium conditions and $\tau_p(t)$ and $\tau_n(t)$ are the time-dependent hole and electron lifetimes. The quantities p_0 and n_0 are the concentrations of holes and electrons under pre-irradiation thermal equilibrium conditions. For low-level injection in an n-type material, $u(x,t)$ is much less than the majority carrier doping for the device and the ambipolar coefficients became approximately those of the minority carrier; D_p, μ_p, and $\tau_p(t)$, respectively. For convenience, we drop the p subscript for the rest of our analysis. We assume the boundary conditions, $u(0,t) = u(L,t) = 0$ with the initial condition $u(x,0) = f(x)$. Under these conditions, the dominant current component in the undepleted n-type region is the minority carrier current. Applying the boundary condition, the current density becomes [4],

$$J_p(t) = \left[qD\frac{\partial u}{\partial x} - qu\mu E \right]\Big|_{x=0} = qD\frac{\partial u}{\partial x}\Big|_{x=0} \tag{2}$$

We choose the leading sign on the right-hand side of the above equation is chosen so that $J_p(t)$ is positive. We solve the above boundary value problem via the substitution $u(x,t) = V(x,t)e^{ax}$, which transforms equation (1) to

$$V_t = DV_{xx} - (Da^2 + \frac{1}{\tau(t)})V + g(x,t)e^{-ax} \tag{3}$$

where $a = \frac{\mu E}{2D}$. The transformed boundary conditions remain type I, homogeneous, while the initial condition becomes $V(x,0) = f(x)e^{-ax}$. The resultant boundary value problem for $V(x,t)$ may be solved by the finite Fourier sine transform [11] and we may back-transform to find $u(x,t)$. We obtain,

$$u(x,t) = \frac{2e^{ax}}{L}\sum_{n=1}^{\infty}\left[\bar{V}_n(0)e^{-D(\alpha_n^2+a^2)t - \int_0^t \frac{1}{\tau(s)}ds} + \int_0^t \bar{G}_n(w)e^{-D(\alpha_n^2+a^2)(t-w) - \int_w^t \frac{1}{\tau(s)}ds}dw \right]\sin(\alpha_n x) \tag{4}$$

where $\alpha_n = \frac{n\pi}{L}$. $\bar{V}_n(0)$ and $\bar{G}_n(w)$ are given by

$$\bar{V}_n(0) = \int_0^L f(x)e^{-ax}\sin(\alpha_n x)dx \tag{5}$$

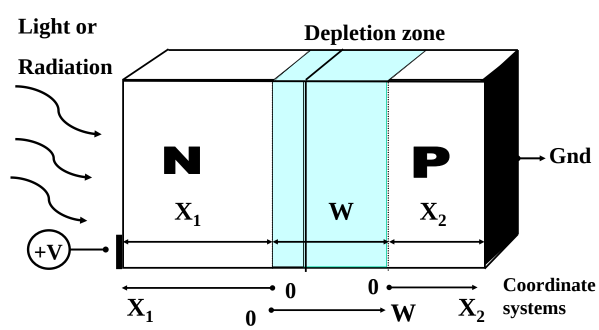

Figure 1: Reverse biased *pn* diode under light or ionizing irradiation. Device is irradiated from the left. For the 1D analysis, the contacts are assumed to cover the entire left and right hand surfaces. The shaded region represents the depletion zone and the unshaded regions represent undepleted zones. The total current is the sum of the drift and diffusion current from the depleted and undepleted zones. Local coordinate systems are shown.

and

$$\bar{G}_n(t) = \int_0^L g(x,t)e^{-ax}\sin(\alpha_n x)dx \tag{6}$$

Equation (4) represents the general solution for the excess carrier density within the undepleted n-type region of the device. The current density evaluated at $x = 0$ is,

$$J_p(t) = \frac{2}{L}\sum_{n=1}^{\infty}\alpha_n\left[\bar{V}_n(0)e^{-D(\alpha_n^2+a^2)t-\int_0^t \frac{1}{\tau(s)}ds} + \int_0^t \bar{G}_n(w)e^{-D(\alpha_n^2+a^2)(t-w)-\int_w^t \frac{1}{\tau(s)}ds}dw\right] \tag{7}$$

Mathematical details will be given in the full paper. We note that the expressions given by equations (4) and (7) may be used to evaluate the excess carrier and current density distributions for an arbitrary function $\tau(s)$. We investigate the effect of an abrupt decrease in minority carrier lifetime, due to a neutron burst, on the photocurrent produced in the non-depleted region of an abrupt junction *pn* diode. The neutron burst is assumed to not be coincident with the initiation of the gamma irradiation. We assume that the gamma pulse is of constant generation density equal to g_0 eh pairs$/cm^2$ from time $t = 0$ until time $t = t_2$, when the pulse drops to zero. The general solution to this problem for a constant minority carrier lifetime is known [8].

The specific (carrier lifetime) case of interest is

$$\tau(t) = \begin{cases} \tau_1 & , \quad t \in [0, t_1) \\ \tau_2 & , \quad t \in [t_1, \infty) \end{cases} \tag{8}$$

For the case where $t_1 < t_2$, $g(x,t) = g_0(1 - H(t - t_2))$, and $H(t)$ denotes the Heaviside function, evaluation of the current density yields,

$$J_p(t) = \frac{2qDg_0}{L}\sum_{n=1}^{\infty}\frac{\alpha_n^2(1-(-1)^n e^{-aL})}{A_n}I(t) \tag{9}$$

in which $A_n = \alpha_n^2 + a^2$ and

$$I(t) = \begin{cases} \frac{1-e^{-DA_n t - \frac{t}{\tau_1}}}{DA_n + \frac{1}{\tau_1}} & , \quad t \in [0, t_1) \\ \frac{e^{-DA_n(t-t_1)-\frac{t-t_1}{\tau_2}} - e^{-DA_n t - (\frac{t_1}{\tau_1}+\frac{t-t_1}{\tau_2})}}{DA_n + \frac{1}{\tau_1}} + \frac{1-e^{-DA_n(t-t_1)-\frac{t-t_1}{\tau_2}}}{DA_n+\frac{1}{\tau_2}} & , \quad t \in [t_1, t_2) \\ \frac{e^{-DA_n(t-t_1)-\frac{t-t_1}{\tau_2}} - e^{-DA_n t - (\frac{t_1}{\tau_1}+\frac{t-t_1}{\tau_2})}}{DA_n + \frac{1}{\tau_1}} + \frac{e^{-DA_n(t-t_2)-\frac{t-t_2}{\tau_2}} - e^{-DA_n(t-t_1)-\frac{t-t_1}{\tau_2}}}{DA_n+\frac{1}{\tau_2}} & , \quad t \in [t_2, \infty) \end{cases}$$

As an example, we use the parameters of Figure 2 in [8]. Specifically, the diffusion length is set at $L_p = \sqrt{D\tau} = 0.015$ and the parameter $L/L_p = 0.32$, corresponding to $\zeta_p = 0.32$ in [8]. The initial minority carrier lifetime is $\tau_p = 10^{-5}s$. A $2.4\mu s$ square wave gamma pulse is assumed to begin at $t = 0$. The gamma irradiation is assumed longer in this example than that of Figure 2 of reference [8] to illustrate the dual steady state photocurrent behavior. A neutron pulse is assumed to cause an abrupt minority carrier lifetime degradation of from one to four orders of magnitude. The neutron pulse occurs at $t = 1.5\mu s$, during the gamma pulse.

Figure 2 gives the computation of the analytic photocurrent density with respect to time for this example. The top (solid) curve assumes the default minority carrier lifetime over the entire pulse length. This curve is labeled $\tau_1 = \tau_2 = 10^{-5}s$. τ_1 is the minority carrier lifetime before the neutron pulse and τ_2 is the lifetime after the neutron pulse. The convergence to a steady current is evident. The photocurrent density curve directly below the top curve corresponds to the case where $\tau_2 = 10^{-6}s$. It is clear that this photocurrent shows a significant decrease when compared with the non-degraded photocurrent over the time spanned after the neutron pulse through the end of the gamma irradiation. The curve corresponding to a degradation of two orders of magnitude, given as $\tau_2 = 10^{-7}s$, shows

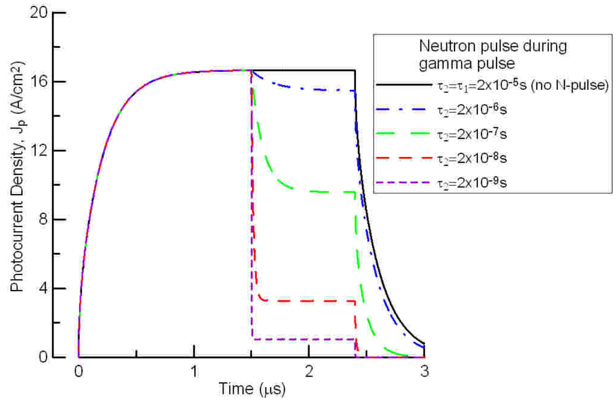

Figure 2: Neutron Pulse during a gamma irradiation.τ_1 is the pre-pulse minority carrier lifetime and τ_2 is the post-neutron pulse minority carrier lifetime.

a more apparent decrease in current (about 40%) to a second steady state associated with this degraded carrier lifetime for the remainder of the gamma pulse. It exhibits a rapid drop to zero during the recovery phase of the gamma pulse. The curves corresponding to $\tau_2 = 10^{-8}s$, and $\tau_2 = 10^{-9}s$ show similar behavior. This example shows a dual steady state behavior resulting from the degraded carrier lifetime. More examples will be given in the full paper.

We present a new transient analytic photocurrent solution for an irradiated (radiation or light pulse) 1D abrupt *pn* junction diode assuming a time-dependent change in carrier lifetime. The photocurrent is developed for the undepleted n-type region and a neutron pulse occurring during irradiation, resulting in an instantaneous reduction of the carrier lifetime in the device. The carrier lifetime is assumed to be spatially uniform, but we are exploring the relaxation of this assumption. An example problem with realistic parameters is analyzed and compared to the analytic solution of a device with no carrier lifetime degradation [8]. Significant reductions in photocurrent occur for lifetime degradations of an order of magnitude or more. Two photocurrent steady states are observed, one associated with the original carrier lifetime and a second associated with the degraded carrier lifetime.

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