ANALYTICAL MODELLING OF A LINEAR GaAS PHOTOCONDUCTIVE SWITCH FOR SHORT PULSE EXCITATION

J.R. Mayes
Applied Physical Electronics, L.C.
602 Explorer Austin, Texas 78734

W.C. Nunnally
The University of Missouri-Columbia
Columbia, Missouri 65201

Abstract

The carrier density for a photoconductive switch is described by a single linear rate equation that is dependent on the time-varying incidental optical source. Typical solutions to this equation assume the optical source as a square pulse with instantaneous rising and falling edges; thus simplifying the solution to the problem. This paper presents an analytical solution to the rate equation with a short, gaussian optical profile. This solution leads to a PSpice model for the photoconductive switch using a time-varying resistor model. The time-dependent conduction profile is numerically generated by the analytical solution and placed in a table definition for the time-varying resistor model. This paper discusses the analytical aspects of the solution and presents the PSpice model results. Analytical and experimental results are compared.

Introduction

Photoconductive switches play an important role in high power, ultrashort pulse applications. The linear photoswitch proves to be advantages in applications requiring an extremely low temporal jitter and pulse-shaping capabilities as with the injection wave generator, IWG. [1,2]

An accurate analytical model of the photoswitch is of paramount importance to understanding the operation of the IWG. This paper briefly describes the physics of the photoswitch, leading to the rate equation used to describe the carrier density of the switch medium, which is dependent on the time variant optical source. An analytical solution, based on a short gaussian optical pulse, completes the physical description of the linear photoswitch. The numerical results of this equation may then be used in PSpice, using a model for a nonlinear resistor.

A basic photoswitch experiment is constructed such that the recombination time of the switch may be determined. Two switch materials are used in this experiment with the results being compared to the simulation model.

This work was funded by the U.S. Army, Contract number DASG60-98-C-0020. Additional support was provided by Sandia National Laboratories.

Background

The photoconductive switch is fabricated from bulk intrinsic semiconductor material. Ohmic, low resistance contacts are placed on the surface (or end) of the material as in Figure 1. Upon illumination, usually with a laser, each photon with sufficient energy to excite an electron into the conduction state is absorbed by the material, thus, creating an electron-hole pair. As the carrier density increases, the resistance of the material decreases, changing the material from an insulator to a conductor. With the removal of the light source, the electron-hole pairs recombine in a time characteristic to the semiconductor, returning the material to its natural state as an insulator. In essence, the conductivity increases as the optical energy is absorbed and decreases as the carriers recombine.

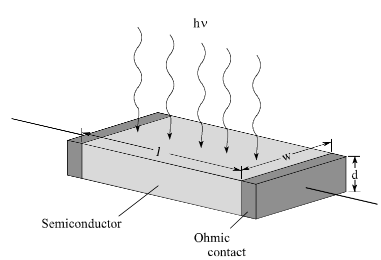

Figure 1. The basic photoswitch.

The conductive state resistance follows from the standard resistance equation, $R = l/(\sigma A)$, where the cross-sectional area, A, may be defined as product of the width, w, of the switch and the penetration depth, de, of the optical source and is a function of the source wavelength. The conductivity of the material is given by

$$\sigma = n_o q \mu_n + p_o q \mu_p \qquad (1)$$

where μ_n and μ_p are the electron and hole mobilities, respectively, n_o and p_o are the initial density states, and q is the electron charge. During illumination, incident photons create electron-hole pairs and the density states increase in population as $n = n_o + n_i$ and $p = p_o + p_i$, where n_i and p_i are the excess electron and hole densities generated by the illumination. Assuming that $n_i >> n_o$ and $p_i >> p_o$, then $n \sim n_i$ and $p \sim p_i$. Furthermore, since one electron-hole pair is generated by each photon, then n = p, and equation (1) becomes

$$\sigma = nq\,(\mu_n + \mu_p) \tag{2}$$

Considering the average mobility to be $\mu = (\mu_n + \mu_p)/2$, then the conductivity may be defined as $\sigma = nq\mu$. Therefore, the conduction resistance becomes

$$R = \frac{l}{nq\mu w d_e} \tag{3}$$

Assuming that the optical energy is delivered as a pulse, the carrier density is a function of time, and the time-rate of change for the carrier density is defined as

$$\frac{dn(t)}{dt} = \frac{P_L(t)(1-r)}{E_\lambda w l d_e} - \frac{n(t)}{T_r} - \frac{(1-\eta)n(t)}{T_t} \tag{4}$$

where $P_L(t)$ is the time–varying incidental power in Watts, r is the material reflectivity at the incidental light wavelength, E_λ is the photon energy, T_r is the material recombination time, η is the contact injection efficiency, and T_t is the carrier transit time.[3] By setting

$$\beta = \frac{1}{T_r} + \frac{1-\eta}{T_t}\,, \tag{5}$$

and

$$\alpha = \frac{1-r}{E_\lambda w l d_e} \tag{6}$$

equation (4) becomes

$$\frac{dn(t)}{dt} + n(t)\beta = P_L(t)\alpha\,; \tag{7}$$

which is a first–order differential equation. The solution for n(t) is found as follows:

$$n(t) = e^{-\beta t}\int_0^t e^{\beta t}\,\frac{P_L(t)(1-r)}{E_\lambda w l d_e}\,dt + N_o\,. \tag{8}$$

Typical solutions to this equation [3] assume long conduction times with respect to the short laser source. In these cases, the optical power is characterized as a square pulse, $P_L(t) = 1$ during conduction and $P_L(t) = 0$ at all other times. This greatly reduces the complexity of equation (8). However, a full characterization of the switch behavior is now made so as to understand the observed switch behavior with short pulse excitation.

Gaussian Excitation Solution

The laser excitation profile may be described by the following equation:

$$P(t) = P_o e^{-4\ln(2)\left(\frac{t-t_o}{\Delta t}\right)^2} \tag{9}$$

where P_o is the maximum power, t_o defines the center of the pulse, and Δt is the full width half maximum (FWHM) of the pulse.[4] Therefore, the photoswitch carrier density equation becomes

$$n(t) = \frac{e^{-\beta t}\,(1-r)\,P_o}{E_\lambda\, w\, l\, d}\int e^{\beta t} e^{-\frac{4\ln(2)}{\Delta t^2}(t-t_o)^2}\,dt + N_0 \tag{10}$$

for which the solution is found to be

$$n(t) = \frac{(1-r)\sqrt{\pi}}{E_\lambda\, w\, l\, d_e}\,\frac{e^{-\frac{\Delta t^2}{\tau^2\,16\ln(2)}}}{4\sqrt{\ln(2)}}\,e^{-(t-t_0)/\tau}\cdot\left\{erf\left[\frac{-\frac{1}{\tau}+\frac{8\ln(2)}{\Delta t^2}(t-t_0)}{4\sqrt{\ln(2)}}\,\Delta t\right]+1\right\} + N_0 \tag{11}$$

This equation may then be inserted back into equation (3) to resolve the time-varying resistance of the photoswitch.

$$R(t) = \frac{l}{q\mu w d_e}\left[\frac{(1-r)\sqrt{\pi}}{E_\lambda\, w\, l\, d_e}\,\frac{e^{-\frac{\Delta t^2}{\tau^2\,16\ln(2)}}}{4\sqrt{\ln(2)}}\,e^{-(t-t_0)/\tau}\cdot\left\{erf\left[\frac{-\frac{1}{\tau}+\frac{8\ln(2)}{\Delta t^2}(t-t_0)}{4\sqrt{\ln(2)}}\,\Delta t\right]+1\right\} + N_0\right]^{-1} \tag{12}$$

Figure 2 provides a numerical demonstration of the material reaction with a gaussian-shaped optical illumination as defined by equation (12). In this case, all the waveforms are normalized, so as to compare the profiles of the conductivity and the switch resistance with the optical illumination. Two of the more outstanding features of this diagram lie in the rise and decay times of the conductivity curve. The rise time appears to continue to rise for the full duration of the optical pulse and recombination of the carriers does not appear to begin until the optical source is removed.

The effect of the material recombination time and its apparent effect on the rising edge of the conductivity profile is tested by superimposing several conductivity waveforms, each marked by a unique recombination time. As shown in Figure 3, not only is the rise time effected, but also is the gain. Intuitively, this should be correct given that the conductivity equation is ultimately described by the density of states rate equation. With faster recombination times, the carriers may recombine at nearly the same rate as they are generated, affecting the peak number of generated carriers; however, with slower recombination times, the number of carriers continually builds even as the number of photons injected into the switch material begins decreasing. Thus, a trade-off between fast material response and gain must be made.

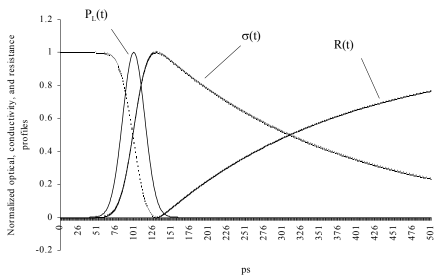

Figure 2. A numerical simulation of the population density equation and resistance of a photoswitch illuminated by a gaussian optical source.

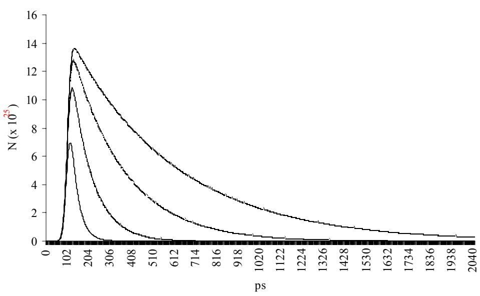

Figure 3. The carrier density profile as a function of material recombination.

The numerical description of the resistance profile of the photoswitch using equation (12) is well suited for the basic understanding of the switch behavior; however, to be useful in circuit applications, the resistance profile needs to be incorporated into a circuit simulation package such as PSpice.

Switch Modelling with PSpice

The behavior of the photoswitch maybe modelled in PSpice using the method presented by Warren, et al. [5] This method utilizes a dependent voltage source to model a time-varying resistance and uses the capability of PSpice to represent dependent sources with polynomials. Warren outlines the Spice implementation for a nonlinear switch as follows:

- use a voltage source of zero volts to measure the load current,
- use a current-controlled voltage source to implement the closing switch,
- use a current source to generate the proper resistance,
- use a sensing voltage source to control the current source. [5]

The voltage source (V_{CVR}) used to measure the load current and the current-controlled voltage source (H_{SWITCH}) combine to form the nonlinear switch in the photoswitch model. An auxiliary circuit formed by three elements, $I_{RESISTANCE}$, R_{SENSE}, and $V_{RESISTANCE}$, generate and sense the resistance profile. $I_{RESISTANCE}$ is specified using a piece-wise linear (PWL) definition, and is specific in time—resistance pairs. Figure 4 provides the basic simulation circuit defining the nonlinear switch as well as the auxiliary reference circuit.

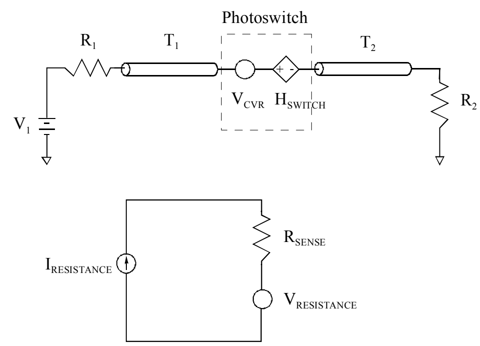

Figure 4. The PSpice model for a linear photoswitch and simulation circuit using a time-varying resistance.

The current source in the auxiliary circuit provides the connection to the photoswitch equation (12). Since a source may be defined as a piece-wise linear device, a point-by-point (time versus resistance) description of the resistance curve may be inserted into the current source definition as shown below,

```
IRESISTANCE  node1  node2  PWL(
        + 1E-12        1.00E+09
        + 2E-12        1.00E+09
        + 3E-12        1.00E+09
```

Experimental Arrangement

The photoswitch model is tested for its characteristic recombination time with the experimental arrangement shown in Figure 5. A 5 ns transmission line is initially charged through a charging resistor and is isolated from the load by the linear photoswitch. The load transmission line is split, with one portion of the signal immediately triggering the SCD5000 while the remaining signal is delayed, via a 47 ns delay line before reaching the digitizer.

The photoswitch is illuminated with a Continuum Nd:YAG laser. This laser produces a 35 ps, 532 nm, 40 mJ pulse, well suited for this study.

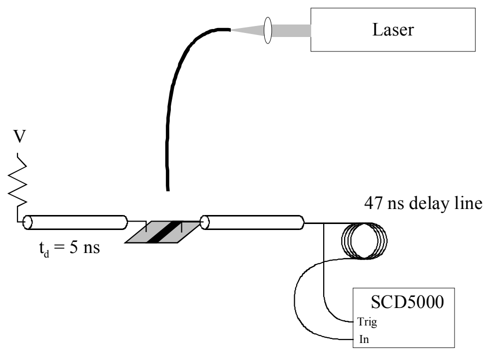

Figure 5. The photoswitch experimental arrangement.

Two switch materials were used for this experiment, an intrinsic GaAs and a chromium-doped GaAs. Each switch was designed for a 1 mm gap spacing and a 5 mm width and were fabricated by Sandia National Laboratories.

Results

Each switch material is tested for its characteristic recombination time with the results being shown in Figures 6 and 7. In each figure, the experimental waveform is superimposed with the simulation waveform for a direct comparison. Interestingly, each material shows two unique recombination times during the switching process

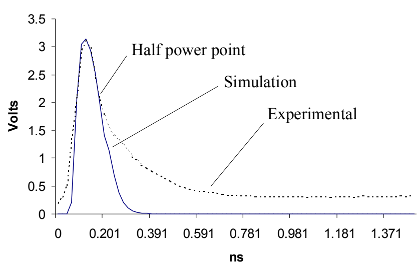

Figure 6. Experimental and simulation results for the first material. Recombination time of 30 ps.

This first material is characterized by a 30 ps recombination time during the initial recombination process. However, at approximately the half power point, the material exhibits a new rate of change, with a recombination time of approximately 300 ps.

The second material, shown in Figure 7, is characterized by a recombination time of approximately 150 ps. Again, the simulation curve closely follows the experimental waveform; however, at the half power point, the recombination rate appears to slow to rate of several nanoseconds.

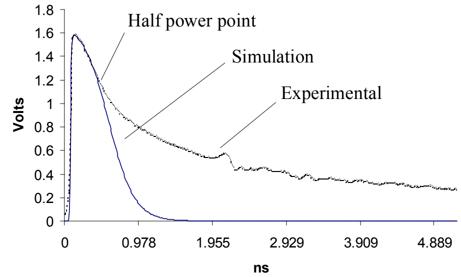

Figure 7. Experimental and simulation results for the second material. Recombination time of 150 ps.

Conclusion

This paper presents the analytical description of the linear photoconductive switch. The solution to the photoswitch's rate equation, based on a short, gaussian optical excitation, successfully describes the behavior of the linear switch and is easily ported into a PSpice model for nonlinear resistive components.

A direct comparison between the simulation results and the experimental results validate the model's usefulness. However, the simulation also pronounces the two-time constant effect seen in the switch, as the simulation curve continues to fall at the prescribed rate while the experimental waveform decays at a new, more gradual rate. The material appears to make this transition at the half power point and may easily be accounted for in the model with the introduction of a second recombination constant.

References

1. W.C. Nunnally, "High-Power Microwave Generation Using Optically Activated Semiconductor Switches," IEEE Transactions on Electron Devices, Vol. 37, No. 12, December 1990.
2. J.R. Mayes, W.J. Carey, and W.C. Nunnally, Experimental Multiple Frequency Injection Wave Generator," The Conference Record for the 22nd Power Modulator Symposium, 1996.
3. W.C. Nunnally, Picosecond Optoelectronic Devices, Ed. C.H. Lee, Academic Press, Inc., New York, 1984.
4. A. Siegman, Lasers, University Science Books, California,, 1986.
5. T. Warren and L. Matheus, "Modeling Non-Linear Pulsed Power Components Behaviors," 8th IEEE International Pulsed Power Conference, San Diego, California, 1991.