Transient Response of High Electric Field Picosecond Photoconductive Switch

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ABSTRACT

A numerical analysis has been performed to investigate the transient response of picosecond photoconductive switches under high electric field bias. For the first time the combined effect of carrier recombination and sweep-out coupled with the effect of velocity overshoot and saturation have been quantitatively analyzed. The simulated results shows that switches operating in the sweep-out regime can be as fast as switches operating in the recombination mode.

I. Introduction

In recent years, picosecond photoconductive (PC) switches have been used for the characterization of ultra-high speed devices [1], [2]. The bandwidth available for these measurement techniques is inversely proportional to the width of the generated electrical pulses. A pulse of the order of 1 ps can produce a bandwidth greater than 1 THz. Different mechanisms have been presented for the generation of picosecond electrical pulses. By using carrier recombination time limited switch, single picosecond electrical pulse has been generated [3]. This simulation suggests that it is also possible to generate single picosecond electrical pulses using switches operating in sweep-out mode. The sweep-out mode can be achieved by reducing the gap length to sub-micron range. In this range, sweep-out dominates recombination and therefore dictates the carrier lifetime. In order to operate in sweep-out mode, the photoconductor is biased at very strong electric field causing the microscopic Ohm's law is no longer be valid. Insofar, there is no quantitative analysis of the behavior of picosecond photoconductivity under such high electric field conditions. In this paper, we present a numerical analysis to investigate the combined effect of carrier recombination and sweep-out, and the effect of velocity overshoot and saturation.

II. Numerical Model

The mathematical model is based on 1-D continuity equations for electrons and holes [4], and Poisson's equation.

$$\frac{\partial E_x}{\partial x} = \frac{\epsilon}{\epsilon}\,(p - n + p_T^+) \qquad (1)$$

where

E_x is the electrical field along the x direction, p and n are the hole and electron concentrations, and p_T^+ is the concentration of the charged recombination centers.

A single donor type recombination center posistioned at the mid-gap is considered. Under picosecond excitation, the population of the charged recombination centers is greatly affected; therefore, the Shockley, Hall and Read recombination rate is no longer valid. We use Eq. 2 to maintain charge continuity at the recombination centers [5].

$$-\frac{\partial p_T^+}{\partial t} = R_n - R_p \qquad (2)$$

where

R_n and R_p are the electron and hole recombination rates.

The material chosen for our simulation is O^+ implanted GaAs. For this material, the capture cross-section for electrons and holes is $\sim 3.7 \times 10^{-14} cm^2$ [6]. The mobility for electrons and holes at low electric field are 2000 and 100 $cm^2/v - s$ respectively. We can determine the field-dependent mobility for electrons [7], and these calculated field-dependent values are shown in Fig.1. Since, only electrons experience velocity overshoot, holes are not included in velocity overshoot calculations in the simulation. Additionally, we ignore the effect of ballistic transport because the mean free path of the electron is about .02 μm and the minimum gap length simulated is .25 μm.

The temporal and spatial shape of the laser beam is assumed to be Gaussian. The excitation rate ranges from 10^{20} to 10^{25} $/cm^3 - s$ which are normally attainable in the laboratory. Since the free carrier concentration generated is less than $10^{13}/cm^3$, dielectric relaxation occurs on a nanosecond time scale. Consequently, the switch operates in the high-field regime throughout the simulation.

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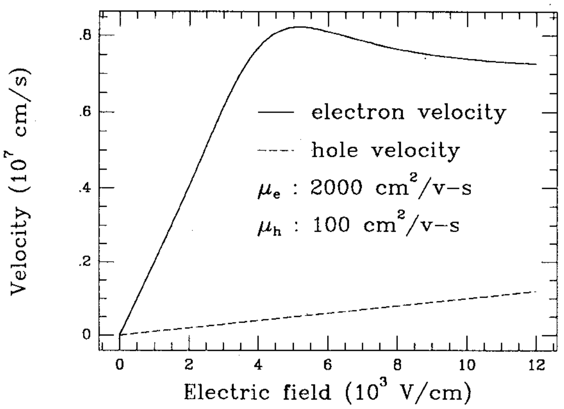

Figure 1 The electron and hole velocities vs. applied electric field. μ_e and μ_h are the low field mobilities for electrons and holes.

III. Results

By operating in the sweep-out mode, we found that the photoconductive lifetime could be reduced to a single picosecond as shown in Fig. 2. This can be achieved, if the biasing electric field remains constant and the gap length is reduced to .25 μm. The short lifetime can be explained by the fact that the electric field in the gap does not collapse in the picosecond time scale; therefore, no low field region exists in the center of the gap to slow the carrier sweep-out process. The excess electron, hole, and charged recombination center concentrations are shown in Fig. 3.

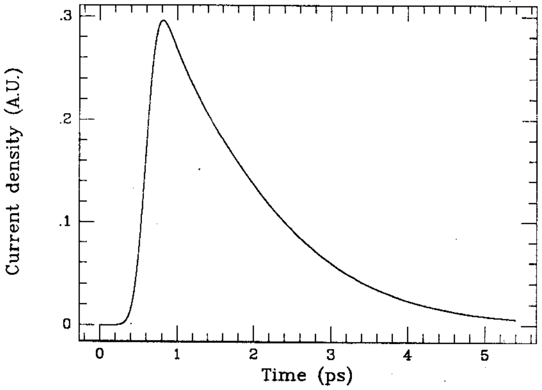

Figure 2 A single picosecond electrical pulse could be generated by operating the switch in sweep-out mode. The gap length is .25 μm.

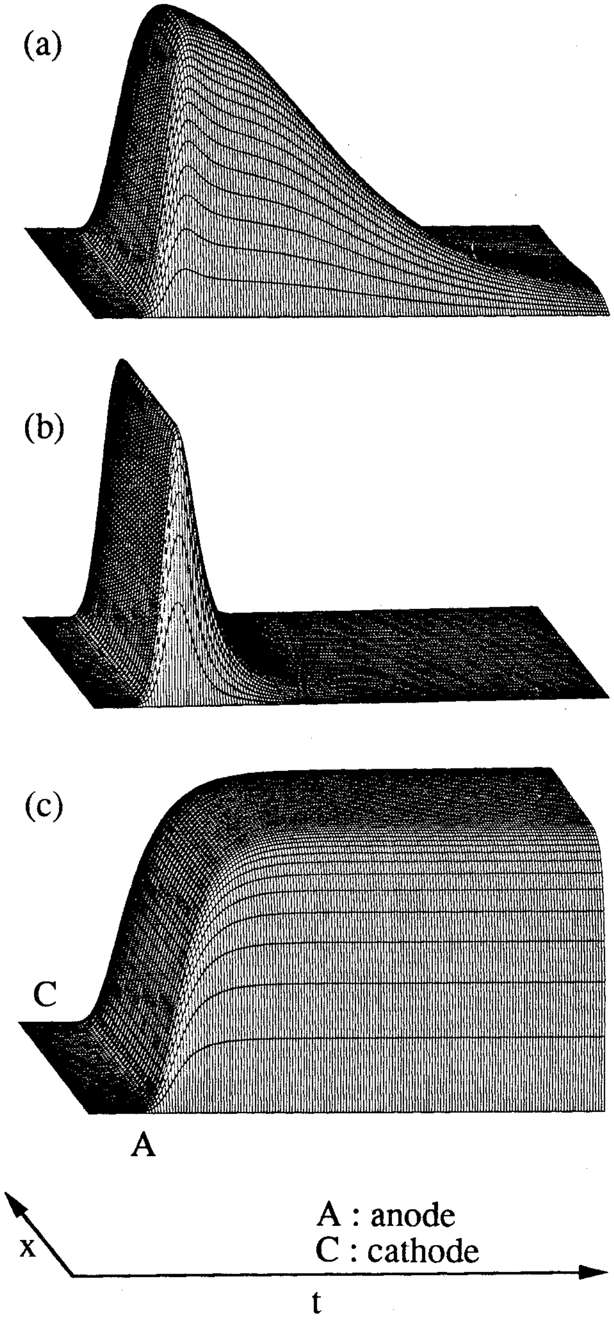

Figure 3 Excess (a) electron (b) hole (c) charged recombination center concentrations. x ranges from 0 to 0.25 μm. t ranges from 0 to 5.4 ps. The anode is at $x=0$.

The relationship between the photoconductive lifetime and gap length for switches with different recombination times is depicted in Fig. 4. We then consider the interplay between the combined effect of carrier recombination and carrier sweep-out. We find that when sweep-out effect dominates the carrier lifetime, the tail of the current transient decays more linearly than exponentially. Figure 5 shows the relationship between the carrier recombination time, sweep-out time, and lifetime. The sweep-out time is defined as the transit time for a carrier to propogate half of the gap length.

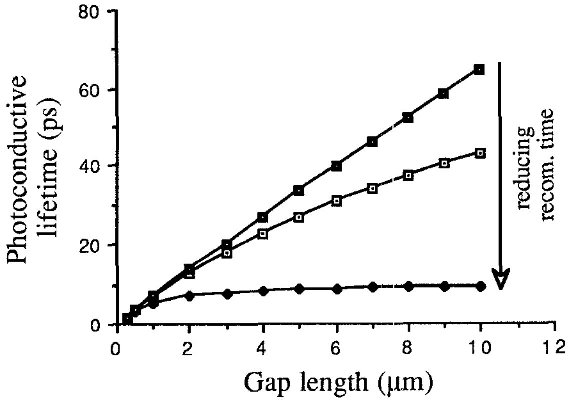

Figure 4 The photoconductive lifetime vs. gap length. Different curves are for switches with different recombination times.

Another phomena which has an effect on the shape of the generated electrical pulse is veocity overshoot. As the electric field is increased to drive the switch into the velocity overshoot region, we find that the pulse's ampltitude is decreased and the pulsewidth is widen as shown in Fig. 6. This effect can be understood by examining the continuity equation for electrons

$$\frac{\partial n}{\partial t} = \frac{\partial(nv_n)}{\partial x} + D_n\frac{\partial^2 n}{\partial x^2} + G - R_n \qquad (3)$$

where
D_n is the diffusion constant for electrons and G is the optical excitation rate.

From the equation above, it is clear the electron distribution is essentially determined by its velocity which is a function of the field dependent mobility and the electric field. Due to velocity overshoot and velocity saturation, the sweep-out time becomes longer, resulting in a wider pulse. The amount of electrons been swept out of the gap is also reduced. This reduces the ratio of electron current to hole current causing the hole current to become visible.

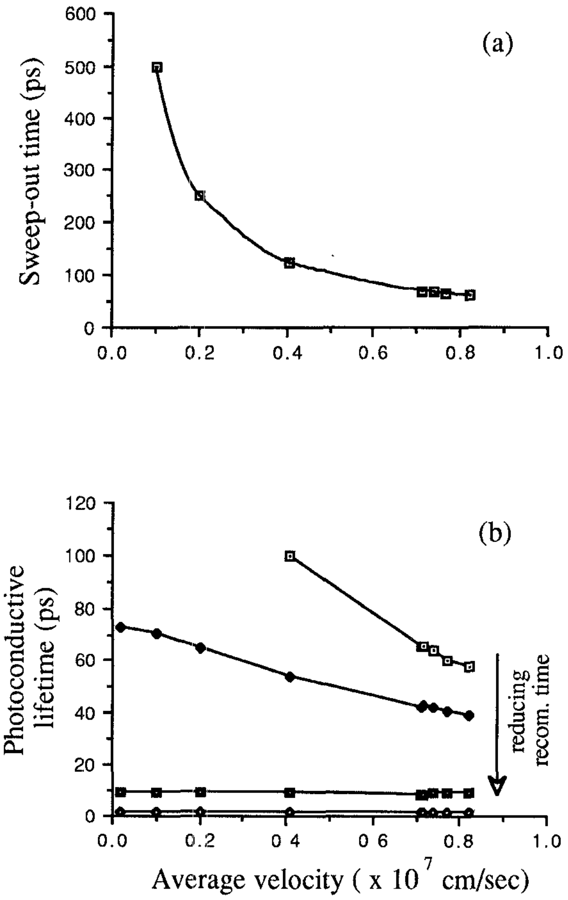

Figure 5 (a) The sweep-out time and (b) the photoconductive lifetime vs. average velocity of electrons. Different curves in (b) are for switches with different recombination times. The recombination times could be obtained from extrapolating the curves to zero average velocity. The gap length is 10 μm.

It is also observed that the pulse width could be reduced by more than an order of magnitude if the laser spot size is small compared to the gap length and the excitation is asymmetrically applied. The simulated result is shown in Fig. 7. This might explain the experimental result in Ref. [8] where a short pulse is generated by using a switch with a long recombination time. Additionally, in that experiment, the interface between the metal and wafer was not perfectly ohmic. If a Schottky contact exists, the sweep-out effect would become even stronger, resulting in even shorter electrical pulses.

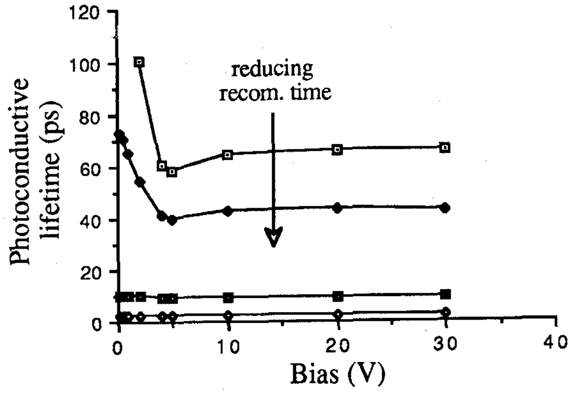

Figure 6 The photoconductive lifetime vs. bias. Different curves are for switches with different recombination times. The gap length is 10 µm.

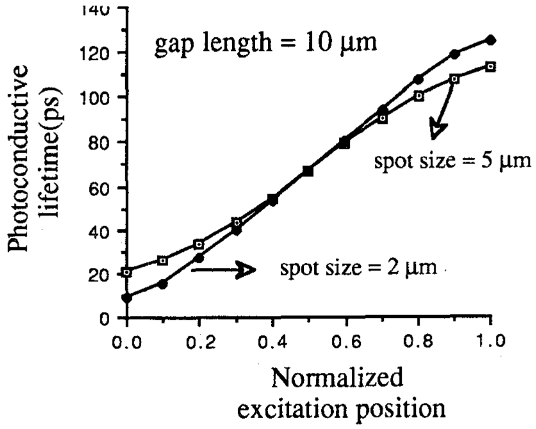

Figure 7 The photoconductive lifetime vs. the position of the excitation spot on the gap. The anode is at position 0.

IV. Conclusion

The understanding of the transient response of a PC switch under a high electric field is important for PC switch design. Our simulation shows that a single picosecond electrical pulse could be generated by the sweep-out effect. A switch utilizing the combined effect of carrier recombination and sweep-out can produce a shorter electrical pulse with higher sensitivity. The ion implantation dose and energy utilized for making fast PC switches can be optimized if a 2-D analysis is performed.

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