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PHYSICS OF SEMICONDUCTOR DEVICES

Avalanche Mode of High-Voltage Overloaded p^+–i–n^+ Diode Switching to the Conductive State by Pulsed Illumination

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Abstract—A simple analytical theory of the picosecond switching of high-voltage overloaded p^+–i–n^+ photodiodes to the conductive state by pulsed illumination is presented. The relations between the parameters of structure, light pulse, external circuit, and main process characteristics, i.e., the amplitude of the active load current pulse, delay time, and switching duration, are derived and confirmed by numerical simulation. It is shown that the picosecond light pulse energy required for efficient switching can be decreased by 6–7 orders of magnitude due to the intense avalanche multiplication of electrons and holes. This offers the possibility of using pulsed semiconductor lasers as a control element of optron pairs.

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1. INTRODUCTION

Recently [1], the author theoretically studied the picosecond switching of high-voltage reverse-biased p^+–n–n^+ structures to the conductive state by a short light pulse. Without going into details, the main result of [1] can be formulated as follows. If the illumination duration t_{ph} is appreciably shorter than the switching time t_k and the light-pulse energy

$$W_{ph} > 2W_0 = 2\xi\frac{\hbar\omega E_0 d^2}{qu_s}, \tag{1}$$

then

$$t_k \approx \tau\frac{W_0}{W_{ph}} = \frac{1}{n_0}\frac{\varepsilon E_0 S_d}{qu_s S_0}, \tag{2}$$

where $n_0 = W_{ph}/\hbar\omega\xi S_0 d$ is the initial electron density averaged over the n-layer thickness d, E_0 is a field strength slightly lower than the breakdown value E_b, $\xi^{-1} = (1 - R_{ph})(1 - e^{-\kappa d})$, $\hbar\omega$ is the photon energy close to the band gap, R_{ph} and κ are the light reflectance and absorbance, $u_s = (u_{sn} + u_{sp})$, $u_{sn, sp}$ are the saturated electron and hole drift velocities, $\tau = R_L C_d$, R_L is the load resistance, $C_d = \varepsilon S_d/d$ is the diode capacitance, S_d is the diode area, q is the elementary charge, and ε is the permittivity of silicon. At the photodiode parameters used in [1], $W_0 \approx 2.4$ μJ and $\tau \approx 100$ ps; hence, efficient control requires light pulses with an energy no lower than 5 μJ and a duration no longer than 50 ps.

Such pulse parameters can be easily achieved using modern commercial neodymium [2] and ytterbium lasers [3] whose photon energy is almost ideal for silicon. However, their high cost, considerable dimensions, and low efficiency are completely unacceptable for many practically important applications. In these parameters, the most appropriate light sources are pulsed semiconductor lasers [4]; however, their present power is lower than the necessary one by 5–6 orders of magnitude for commercial [5] and by 3–4 orders of magnitude for record (experimental) [6] prototypes. In the present paper, we consider one of the possible resolutions of this inconsistency. It will be shown that the use of strongly overloaded (i.e., reverse biased to a voltage of $U_0 = (1.5–2.5)E_b d$) high-voltage p^+–i–n^+ photodiodes (which we call avalanche photodiodes (APDs)) makes it possible to decrease the value of W_{ph} required for efficient switching by 6–7 orders of magnitude due to the very intense avalanche multiplication of electrons and holes generated by a picosecond light pulse.

2. ANALYTICAL THEORY

Let us consider the switching of an APD connected to a voltage source through series resistance R_L. Let the intrinsic concentration $n_i \ll \tau_g u_s/d^2 S_d$ (τ_g is the generation lifetime). This condition[1] provides the complete absence of electrons and holes in the depleted i layer before the beginning of illumination and the possibility of reaching significant overvoltage without diode breakdown in a time d/u_s on the order of several nanoseconds. The equipment necessary for this has long been developed, see, e.g., [7]. Once the voltage U at the APD reaches $U_0 = (1.5–2.5)E_b d$, it is illuminated

[1] For typical parameters, it is satisfied at $T \leq 200$ K for silicon and $T \leq 660$ K for 4H-SiC.

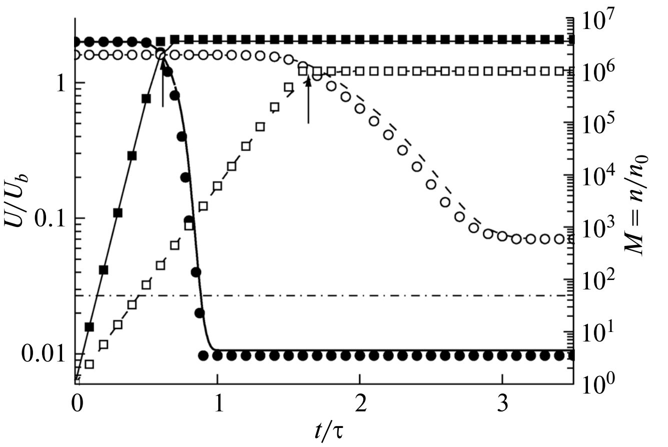

Fig. 1. Time dependences of the APD voltage (circles) and the multiplication factor (squares), obtained by exact (curves) and approximate (symbols) solutions of the problem (4)–(6) at $d = 250$ μm, $U_b = 3.6$ kV, $n_0 = 10^9$ cm^{-3}, $\tau = 200$ ps, and two values of U_0, $U_0 = 2U_b$ (solid curves and closed symbols) and $U_0 = 1.6U_b$ (dashed curves and open symbols). Arrows indicate the time points t_1. The dash-dotted line indicates the voltage at which $E = E_{sn} \approx 0.4E_{sp}$.

by a light pulse and the switching process begins. The basic equation which describes it is written as [1]

$$C_d\frac{dU}{dt} = \frac{U_0 - U}{R_L} - S_0\bar{j}, \tag{3}$$

where S_0 is the illuminated APD area and $\bar{j}$ is the electron and hole current density in the illuminated area, averaged over the i layer thickness. Strictly speaking, to calculate the function $\bar{j}\,(t)$, we should solve Eq. (3) together with the Poisson equation and continuity equations for the electron $n(t, x)$ and hole $p(t, x)$ densities taking into account intense impact ionization. The strong nonlinearity of this problem excludes the possibility of its exact analytical solution. However, it contains several potentially small parameters, which makes it possible to drastically simplify the situation. We further assume that

(i) the light-pulse duration $t_{\rm ph}$ is much shorter than the switching delay time (see below);

(ii) the charged-impurity concentration in the i layer is negligible;

(iii) the light-absorption length κ^{-1} in the i layer is much smaller than its thickness d;

(iv) the duration of the entire switching process is much shorter than d/u_x.

In this case, the field strength E and carrier concentration $n = p$ are independent of coordinates almost in the entire undoped i layer [1]. Therefore, Eq. (3) can be replaced by

$$\frac{dE}{dt} = \frac{E_0 - E}{\tau} - \frac{S_0}{S_d}\frac{qnu}{\varepsilon} \tag{4}$$

and complemented by the single equation

$$\frac{dn}{dt} = n\nu, \tag{5}$$

where $\nu = (\nu_n + \nu_p)$, $\nu_{n,p}$ are the frequencies of impact ionization by electrons and holes, $u = (u_n + u_p)$, $u_{n,p}$ are the electron and hole drift velocities. The first initial condition for these equations

$$E(0) = E_0 \tag{6}$$

means that the diode capacitance has no time to be recharged by the current qun_0S_0 in the illumination time, and the second condition is written as

$$n(0) = n_0, \tag{7}$$

When using even the simplest approximations for the functions $u_{n,p}(E)$ and $\nu_{n,p}(E)$,

$$u_{n,p} = u_{sn,sp}E(E + E_{sn,sp})^{-1},$$

$$\nu_{n,p} = \tilde{\alpha}_{n,p}u_{sn,sp}\exp(-\tilde{E}_{n,p}/E),$$

(here $E_{sn,sp}$, $u_{sn,sp}$, $\alpha_{n,p}$, $E_{n,p}$ are the fitting parameters whose values for silicon are given, e.g., in [8, 9]), Eqs. (4) and (5) can be solved only by numerical methods. Examples of such solutions are shown in Fig. 1 (curves). Hereafter, we present the results of specific calculations for the silicon APD at $T = 200$ K, $R_L = 50\ \Omega$, $\kappa = 5$ cm^{-1}, $R_{\rm ph} = 0.5$, $S_d = 9.44$ mm^2, and $S_0 = 0.5S_d$. The parameters U_0, d (or U_b), and n_0 (or $W_{\rm ph}$) are variables.

We can see that the entire switching process is divided into two qualitatively different stages. At $t < t_1$, the APD voltage is almost unchanged; therefore, $\nu(E) \approx \nu(E_0) \equiv \nu_0$ in Eq. (5) and $u(E) \approx u(E_0) \approx u_s$ in Eq. (4). Taking this into account, we obtain the solution

$$n(t) = n_0\exp(\nu_0 t), \tag{8}$$

$$E(t) = E_0 - \frac{qS_0R_Lu_sn(t)}{d} \times \frac{1 - \exp[-(\nu_0 + 1/\tau)t]}{1 + \tau\nu_0} \tag{9}$$

which remains valid until[2]

$$\frac{\tilde{E}}{E} - \frac{\tilde{E}}{E_0} < \delta \approx 1$$

[2] The approximate theory described in what follows is best consistent with the exact solution to Eqs. (4) and (5) as δ is varied within (0.8–1). It is clear that this uncertainty is associated with the uncertainty of the choice of $\tilde{E}$ between $\tilde{E}_n$ and $\tilde{E}_p$. We performed specific calculations at $\tilde{E} = \tilde{E}_n$ and $\delta = 0.9$; however, to simplify the subsequent formulas, we suppose that $\delta = 1$.

and the impact-ionization rate will not notably decrease. At $t = t_1$, this inequality becomes an equality, from which

$$E(t_1) \equiv E_1 = \frac{E_0 \tilde{E}}{\tilde{E} + E_0}. \quad (10)$$

Combining Eqs. (8)–(10), it can be shown that

$$t_1 = \nu_0^{-1} \ln M_1, \quad (11)$$

and the electron (and hole) density at $t = t_1$ is given by

$$n_0 M_1 \equiv n_1 = \frac{E_0^2}{\tilde{E} + E_0}\left(\frac{1}{\tau} + \nu_0\right)\frac{S_d}{S_0}\frac{\varepsilon}{q u_s}. \quad (12)$$

In deriving these formulae, we neglected the terms $\exp[-(\nu_0 + 1/\tau)t_1]$ in Eq. (9), which are always smaller than M_1^{-1}. During this stage, the current $I = (U_0 - U)/R_L$ exponentially increases with time; however, the voltage drop at the load IR_L remains much smaller than $U \approx U_0$.

Therefore, time t_1 is in fact the switching delay time. It is interesting to note that the final electron and hole densities $n_1 = n_0 M_1$ are independent of n_0. The avalanche multiplication coefficient M_1 exponentially increases with increasing overvoltage and can be very high (see Fig. 2).

At $t \approx t_1$, the carrier concentration very rapidly increases, while the ionization rate decreases. Therefore, almost immediately after the end of the delay stage, the second stage begins, during which $n(t) \approx M_1 n_0$ and the field strength is even higher than $E_{sn,sp}$, and $u \approx u_s$ as before. In this case, the solution to Eq. (4) with the "initial" condition (10) is written as

$$E(\theta) = E_1\left[1 - \frac{E_0}{\tilde{E}}\tau\nu_0\left(1 - \exp\frac{t_1 - t}{\tau}\right)\right]. \quad (13)$$

It can be used at all $t > t_1$, if the final field strength

$$E(\infty) = E_1\left(1 - \frac{E_0}{\tilde{E}}\tau\nu_0\right) = E_0\frac{\tilde{E} - E_0\tau\nu_0}{\tilde{E} + E_0} \quad (14)$$

is larger than $E_{sn,sp}$, i.e., at

$$\tau\nu_0 < \frac{\tilde{E}}{E_0}\left(1 - \frac{E_{sn,sp}}{E_0}\right) \approx \frac{\tilde{E}}{E_0}. \quad (15)$$

In strong fields, this inequality is not satisfied; the condition $E > E_{sn,sp}$ is violated at

$$t = t_s \approx t_1 - \tau \ln(1 - \tilde{E}/E_0\tau\nu_0),$$

after which the field strength readily approaches

$$E(\infty) = \frac{u_s}{\mu}\frac{1 + \tilde{E}/E_0}{1 + \tau\nu_0} < E_{sn,sp} \quad (16)$$

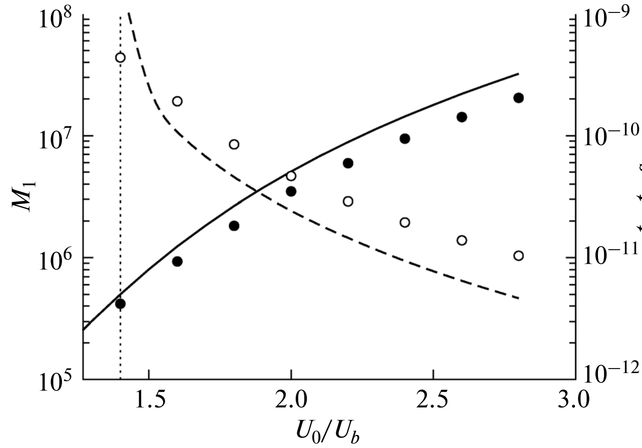

Fig. 2. Dependence of the multiplication factor M_1 (solid curve and closed symbols), durations of the second switching stage t_2 (dashed curve) and the "engineering" switching time t_e (open symbols) on the overvoltage U_0/U_b at d = 250 μm, U_b = 3.8 kV, $n_0 = 10^9$ cm^{-3} or W_{ph} = 1.5 pJ. Symbols are results of the exact solution of Eqs. (4) and (5), the solid curve is the calculation by formula (12), the dashed curve is the calculation by formula (18). The vertical dashed line indicates the value of U_0/U_b at which condition (15) is violated.

and the second stage is completed. In this case, almost the entire source voltage (forming lines) is redistributed from the APD to the load through which the current

$$I_M = \frac{U_0 - E(\infty)d}{R_L} \quad (17)$$

flows. If inequality (15) is satisfied, the duration of this stage is $t_2 \sim 2\tau$; in the opposite most interesting case,

$$t_2 = t_s - t_1 \approx -\tau \ln(1 - \tilde{E}/E_0\tau\nu_0). \quad (18)$$

At sufficiently large overvoltages, when $E_0\tau\nu_0 \gg \tilde{E}$,

$$t_2 \approx \frac{\tilde{E}}{E_0\nu_0} \approx \frac{1}{n_1}\frac{\varepsilon E_0 S_d}{q u_s S_0} \quad (19)$$

and t_2 is independent of the APD parameters, load resistance, and n_0 (see formula (12)). However, the dependence of t_2 on $n_1 = n_0 M_1$ coincides exactly with Eq. (2). This identity reflects the fact that proper switching (stage 2) by the overloaded photodiode occurs exactly as described in [1], but does not begin immediately after the end of illumination, but in the delay time t_1 required to increase the initial concentration n_0 by a factor of M_1 due to intense impact ionization. The example of the dependence of t_2 and the "engineering" switching time[3] is shown in Fig. 2.

[3] It is the time in which the load current increases from $0.1 I_M$ to $0.9 I_M$.

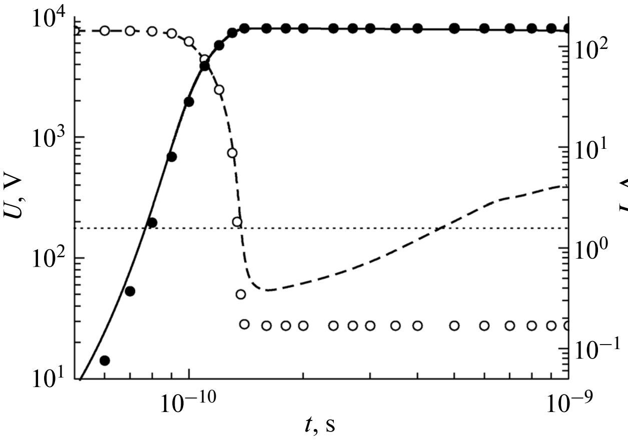

Fig. 3. Time dependences of the current through the load (solid curve and closed symbols) and the APD voltage (dashed curve and open symbols), obtained by solving the problem (4)–(6) (symbols) and accurate numerical simulation (curves) for $d = 250$ μm, $U_b = 3.8$ kV, $U_0 = 2U_b$, and $n_0 = 10^9$ cm^{-3}. The horizontal dashed line indicates the voltage $E_{sn}d$.

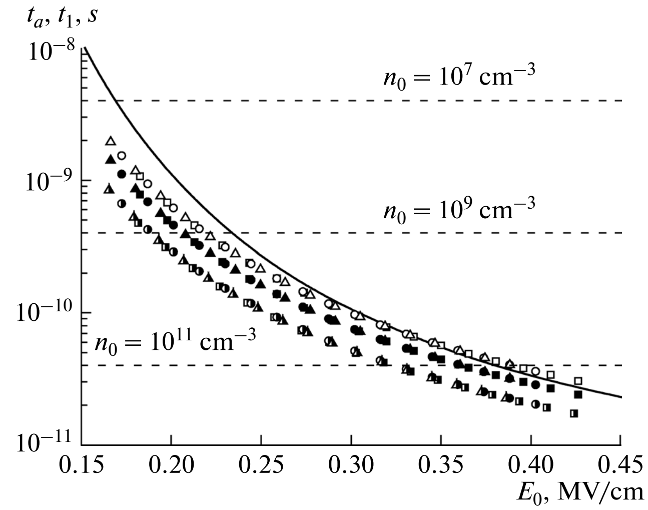

Fig. 4. Dependences of the avalanche–streamer transition time t_a (curve, according to [9], $T = 300$ K) and the switching delay time t_1 (symbols, calculation by formula (11)) on the field strength E_0 at $n_0 = 10^7$ cm^{-3} (open symbols), 10^9 cm^{-3} (closed symbols), 10^{11} cm^{-3} (open–closed symbols), and $d = 150$ μm (squares, $E_b = 151$ kV/cm), 250 μm (circles, $E_b = 143$ kV/cm), 350 μm (triangles, $E_b = 138$ kV/cm). Dashed lines indicate the avalanche overlap time t_{0V} calculated by formula (20) at $D = 10$ cm^2 s^{-1} and various n_0.

3. RESULTS AND DISCUSSION

A comparison of the results of the exact and approximate solutions to Eqs. (4) and (5) (Figs. 1 and 2) shows that formulas (12)–(18) quite well describe the switching process. In turn, the results of the exact solution to Eqs. (4) and (5) are in excellent agreement with the results of numerical simulation using the "Investigation" program [10] (see Fig. 3) up to the actual switching end. However, the approximate calculation of $E(\infty)$ yields a grossly underestimated residual voltage. The reason is that Eqs. (4) and (5) disregard (in view of inequality $t \ll d/u_s$, see above) depletion of the i-layer interfacial regions by carriers drifting to the i-layer depth [1]. The thickness of these regions is small; however, the space-charge density in them (on the order of qn_1) is high, hence, the sum of the "cathode" and "anode" voltages can exceed $E(\infty)d$ even at $t \sim t_1 \ll d/u_s$. The additional (but typically insignificant [1]) contribution to the residual voltage yields the longitudinal spreading resistance of the p^+ layer in the photodiode window.

One more limitation of the applicability of the results is that they were obtained in the continuous approximation which is violated at sufficiently low n_0. Indeed, by the time t, the volume of each avalanche generated by one electron or hole reaches $4\pi D u_s t^2$, where D is the transverse diffusion coefficient. These avalanches are overlapped at

$$t = t_{0V} = (4\pi n_0 D u_s)^{-1/2}. \quad (20)$$

If $t_{0V} < t_1$, the continuous approximation is certainly applicable. This condition is violated at high overvoltages, since the delay time decreases as the initial field strength E_0 increases (see Fig. 4). However, if the average distance between avalanches $(2n_0)^{-1/3} \ll d$, but the avalanche-to-streamer transition time $t_a > t_1$, the continuous approximation is still applicable, although with lower accuracy. The dependence $t_a(E_0)$ for Si at 300 K, obtained in [9], is well described by the function

$$t_a = t_{a0}\exp(E_a/E), \quad (21)$$

where $t_{a0} = 1.0$ ps and $E_a = 1.37$ MV/cm. At 200 K, the parameter E_a should be decreased approximately by 7%. The dependence $t_a(E_0)$ corrected in such a way is shown in Fig. 4. We can see that avalanches can transform into a streamer only at very high overvoltages ($U_0 \geq 2U_b$) and low initial concentrations ($n_0 \leq 10^7$ cm^{-3}). But if $n_0 \geq 10^9$ cm^{-3}, all conditions of theory applicability appear satisfied at $U_0 \leq 3U_b$.

Thus, it can be expected that the use of the avalanche mode of high-voltage photodiode switching allows the application of commercial [5] picosecond semiconductor lasers for diode control. As an example illustrating the capability of this mode, we present an estimate for a device with $d = 250$ μm, $U_b = 3800$ V, and $U_0 = 2U_b$. Upon exposure to a light pulse with a duration less than 20 ps, an energy of 1.5 pJ, and an absorbance of 5 cm^{-1}, such a photodiode should form a pulse with a power of ~1 MW, a delay of 100 ps, and a front time of 46 ps at an active 50-Ω load. Even more impressing results can be obtained using 4*H*-SiC photodiodes (whose operating temperature and breakdown field are approximately three and ten times, respectively, higher than those of silicon diodes) controlled by light with a wavelength of 375 nm.

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