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Amplitude and timing properties of a Geiger discharge in a SiPM cell

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ABSTRACT

The amplitude and timing properties of a Geiger discharge in a stand-alone SiPM cell have been investigated in detail. Use of a single stand-alone SiPM cell allows us to perform measurements with better accuracy than the multicell structure of conventional SiPMs. We have studied the dependence of the output charge and amplitude from an SiPM cell illuminated by focused light vs the number of primary photoelectrons. We propose a SPICE model which explains the amplitude over saturation (when the SiPM's amplitude is greater than the sum over all cells) characteristics of SiPM signals for more than one initial photoelectrons. The time resolutions of a SiPM cell have been measured for the case of single (SPTR) and multiphoton light pulses. The Full Width Half Max (FWHM) for SPTR has been found to be at the level of 30 ps for focused and 40 ps for unfocused light (100 μm cell size).

1. Introduction

Silicon Photomultipliers (SiPM) are intrinsically very fast photodetectors because the Geiger discharge inside a tiny depletion region has very fast build-up and quench times.

However, the single photon time resolution (SPTR) of a $3 \times 3\ \text{mm}^2$ SiPM for unfocused light (~200 ps, left scale of Fig. 1) is much worse than that of a single stand-alone SiPM cell of identical topology using a 2 μm light spot focused on the center of the cell (~30 ps, right scale of Fig. 1) [1].

Thus we studied the SPTR distribution of a single stand-alone cell to observe the time structure of a Geiger discharge development more clearly and deeply than is otherwise possible with a conventional multicell SiPM. Studies of a stand-alone cell also allow us to clarify recently observed oversaturation behavior of SiPM amplitude signals [2], which seems to be in contradiction with the well-known saturation model of SiPM's, at short laser pulse detection, based on the assumption of binary cell operations and the expected binomial statistics of fired cells:

$$n = N \times \left[1 - \exp\left(-\frac{N_{phot} \times \text{PDE}}{N}\right)\right] \qquad (1)$$

where N is the total number of cells inside the SiPM, n is the number of fired cells, N_{phot} is the number of photons and PDE is the light detection efficiency of a SiPM.

2. Amplitude and timing properties of a Geiger discharge in a SiPM cell

2.1. SPICE model of a Geiger discharge development

A Geiger discharge development determines the amplitude and timing properties of a SiPM. An SiPM single cell signal is a function of the discharge process itself and an SiPM's distributed electrical parameters (the cell's and parasitic capacitance, resistance, inductance) including the cell interconnection realization.

As far as we know, thus far no SPICE model for the simulation of a Geiger discharge development in an SiPM cell exists in the literature. The standard approach is to use Corsi SiPM model [3], employing a current source as a Dirac delta impulse to simulate the avalanche process. However, model does not correctly reproduce the rising edge of a SiPM cell pulse [4,5].

The scenario for the Geiger discharge development in an SPAD cell has been proposed in [6]. According to this approach the Geiger discharge in an SiPM cell begins after the appearance of free carriers (electron–hole pairs) in the high field zone of a depletion region from a submicron initial spot with a longitudinal build-up of the avalanche process. During this phase, the local spot current, after a certain

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number of generations of ionization events, reaches quasi-stationary conditions which are themselves determined by the overvoltage applied to this spot. The discharge then expands by extending to boundary regions due to multiplication-assisted diffusion (Fig. 2).

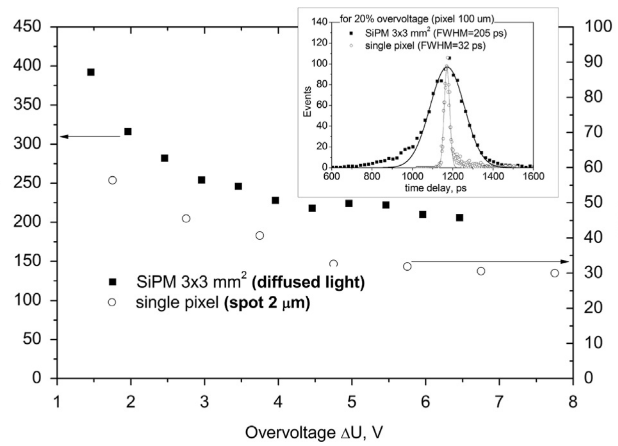

Fig. 1. SPTR for 3×3 mm^2 SiPM and single standalone cell with equal topology and 100×100 μm^2 cell size (20% V_{ov}).

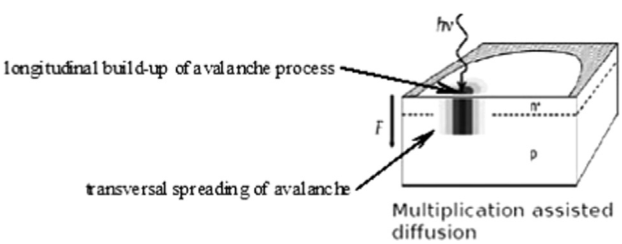

Fig. 2. Models of discharge propagation in a SPAD.

This lateral expansion lasts as long as the $p-n$ junction overvoltage supports continued ionization (note that the overvoltage inevitably drops due to discharge of a cell's capacitor by the avalanche current). According to results obtained by our group using light emission microscopy, the discharge spot is spread out to a lateral scale of approximately 10 μm [7].

All these processes are incorporated in the Dolgoshein–Pleshko Geiger discharge lateral development SPICE model (Fig. 3):

- A Geiger discharge starts from an elementary spot ("start disk") inside a cell.
- Within the start disk, a carrier density equal to $J_0 = k_J \times V_{ov}^0$ is established, where $V_{ov}^0 = V_{ov}(t=0)$ is the initial overvoltage. The parameter k_J may be physically interpreted in terms of the space-charge conductivity per junction area unit [6].
- Space charge effects uniformly lower the electric field inside the cell owing to the very small spreading resistance of the cell surfaces.
- The overvoltage V_{ov}^1 at time $t_1 > 0$ falls below V_{ov}^0.
- At the same time (t_1) the 1st elementary ring begins to fire. Its current density (and disk current density at the time moment t_1) assumes the value $J_1 = k_J \times V_{ov}^1 < k_J \times V_{ov}^0$.
- The process then repeats itself, until the overvoltage and the cell current falls to zero 0. During this process, the instantaneous current density is given by $J(t) = k_J \times V_{ov}(t)$.
- The discharge spreads from the spot with velocity $u(t) = u_0 \times V_{ov}(t)/\ V_{ov}^0$. Here u_0 is the initial velocity, which is independent of the initial overvoltage. This velocity relationship agrees with the current experimental data, according to which the final spot size is independent of the initial overvoltage [7].

Using these relations for the specific current density and lateral speed, it is straightforward to obtain an expression for the total cell current:

$$I(t) = J(t)S(t) = J(t) \times \pi r^2(t) = \pi k_J V_{ov}(t) \left[\int_0^t u_0 \frac{V_{ov}(t')}{V_{ov}^0} dt' \right]^2 \quad (2)$$

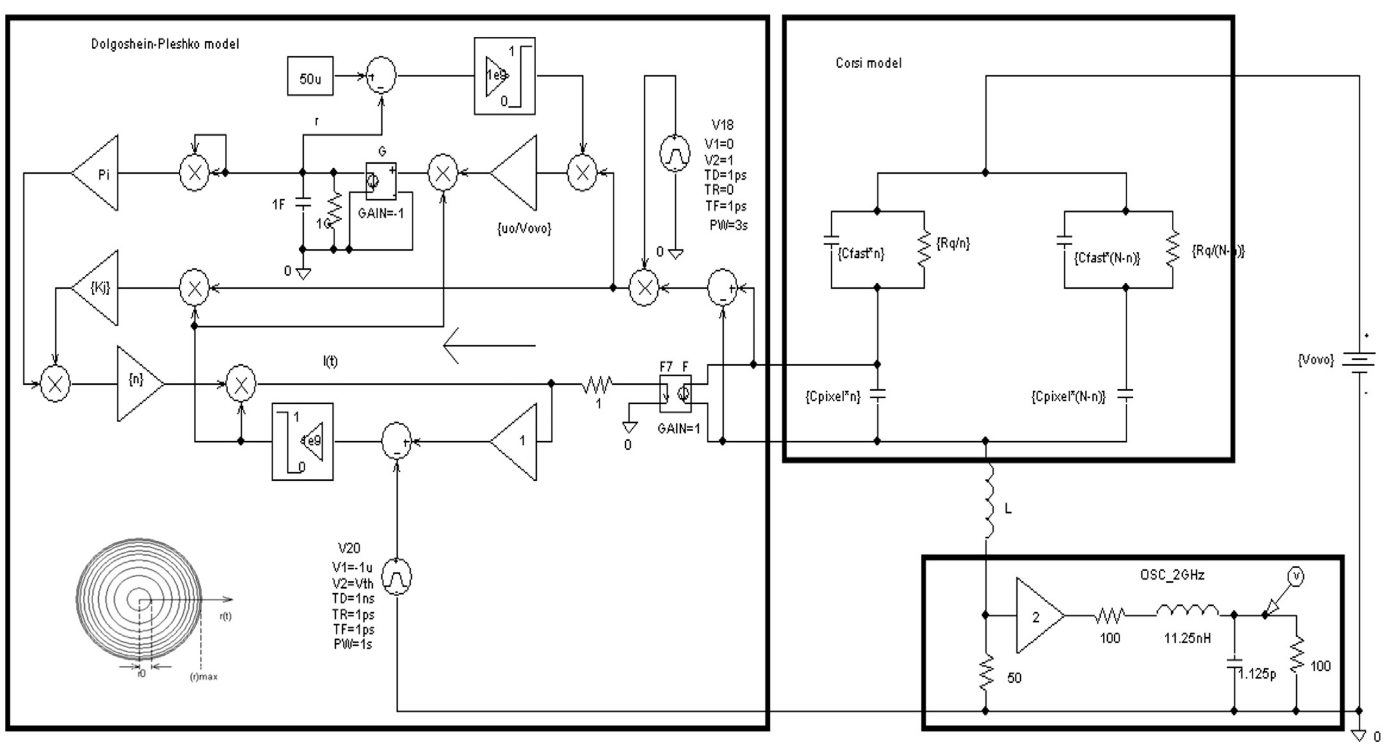

Fig. 3. Dolgoshein–Pleshko SPICE model for Geiger discharge in a SiPM cell.