Monte Carlo study of Single Photon Avalanche Diodes: quenching statistics

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Single Photon Avalanche Diode (SPAD) is a reverse biased p-n or p-i-n junction, with an applied voltage V_d higher than the breakdown voltage V_B. Under such conditions, an electron-hole (e-h) pair generated by photon absorption (photo-generation) can be heated by the electric field, triggering impact ionization and generation of new e-h pairs. This avalanche phenomenon induces a strong increase of the diode current that is set to detect photon absorption. To detect another photon, The SPAD must be reset thanks to a quenching circuit, e.g. an RC circuit, able to stop the avalanche process and remove all excess e-h pairs. Astonishingly, the avalanche phenomenon in SPAD which is by nature a particle and stochastic effect has been rarely studied using particle Monte Carlo (MC) Simulation[1,2]. In particular the quenching process has never been considered using such tools as far as we know

In this work, a self-consistent 3D Monte Carlo algorithm is used to simulate SPAD in series with a passive quenching RC circuit, as shown in Fig.1. With this strategy, all stochastic features of quenching properties can be explored in details, including quench probability and last ionization time.

Once the device was set to steady state for a given V_{bias}, a free e-h pair was generated at a selected position X_{GEN} at $t = 0$, simulating a photon absorption. In Fig. 2 are plotted the time evolution of the number of impact ionization events, the current and the voltage across the SPAD connected to a quenching circuit. The results are shown for four different random choices of wave vectors of the initial e-h pair. Blue and pink curves correspond to a successful quench, whereas red and green curves are typical examples of non-successful quench. Fig. 3 shows the time to avalanche T_A and the breakdown probability as a function of R_Q while Fig. 4 shows the quenching probability and the extinction time T_{EXT} that is defined as the time between T_A and the last ionization event when the SPAD quenches. Remarkably, this probability changes from 0% for $R_Q = 300\,\text{k}\Omega$ to 100% for $R_Q = 1.3\,\text{M}\Omega$. This agrees with the idea that the quenching resistance must be high enough to obtain a successful quench [3]. This self-consistent MC approach turns out to be a powerful tool to investigate all statistical aspects of SPAD operation.

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[2] D. Dolgos et al., J. Appl. Phys., vol. 110, 084507 (2011)
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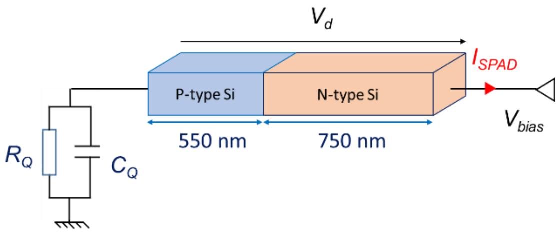

Fig.1: Sketch of simulated device in series with the external passive quench circuit (R_Q,C_Q).

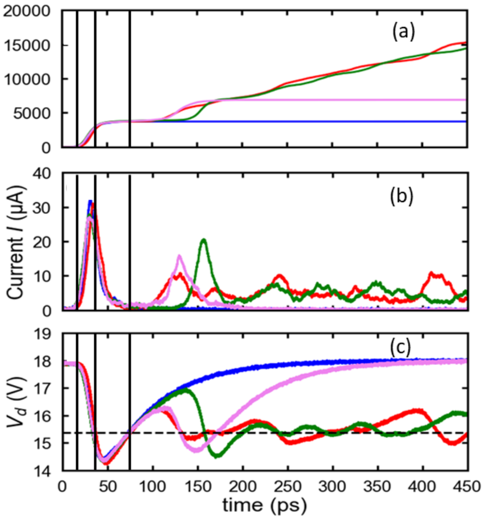

Fig.2: (a) Time evolution of the cumulated number of impact ionization events (II) for four different random choices of wave vectors of the initial e-h pair generated at t = 0 with a quenching circuit (R_Q = 500 kΩ, V_{bias} = 18 V, X_{GEN} = 500 nm). (b) Corresponding time evolution of terminal current. (c) Corresponding time evolution of the SPAD voltage V_d

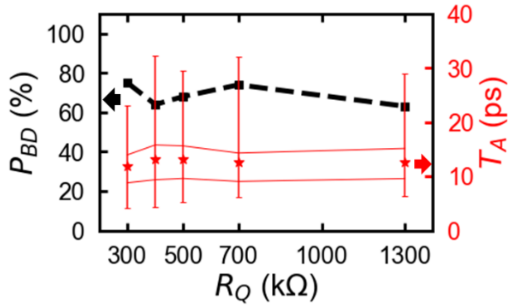

Fig.3: Avalanche time T_A (red stars) and breakdown probability (black squares) versus quenching resistance R_Q. Red stars are mean values of T_A, while vertical bars indicate minimum and maximum values. Half of the values are in the closed area.

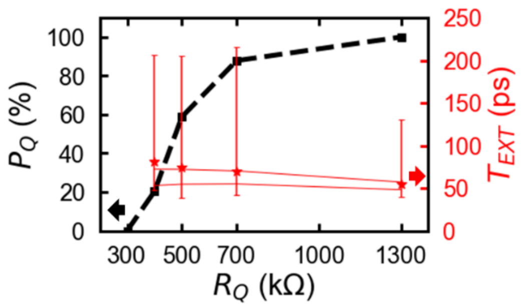

Fig.4: Extinction time (red stars) and quenching probability (black squares) versus R_Q. Red stars are mean values, vertical bars indicate minimum and maximum values. Half of the values are in the closed area.

ISBN 978-89-89453-30-7