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Characterization of Radiation Damaged SiPMs

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SiPMs with 4384 pixels of 15 µm x 15 µm produced by KETEK have been irradiated with reactor neutrons to fluences between 10^9 and 5 10^14 cm-2. After the irradiation C-V, I-V, and current transients with and without pulsed light have been performed at +20℃ and −30℃. No annealing, in addition to the annealing during the transport and the measurements, has been applied. Outside of the measurements the SiPMs were stored at −25℃
From the C−V measurements at 26 V, which were taken at 25 frequencies between 100 Hz and 2 MHz, the SiPM electrical parameters, the pixel capacitance, Cpix, the quenching resistance Rq and the capacitance Cq parallel to the quenching resistor, have been determined using a simple R−C model. It is found that the value of Cpix neither depends on dose nor on neutron fluence, whereas the value of Rq increases for fluences above 10^12 cm-2. As expected for a poly-Si resistor, Rq also increases with temperature. The frequency dependence of the measured complex resistance at high fluences shows effects of radiation-induced defects. The C−V measurements at a fixed frequency have been used to investigate the doping profile and electric field of the SiPM. Indications for a small decrease of the electric field in the vicinity of the p+n junction are found, which are attributed to donor (P) removal.
The I−V data without illumination are used to determine the breakdown voltage, Vbd. We note that for the SiPMs investigated, we found previously that the breakdown voltage determined from the I−V data is approximately 1 V higher than the voltage obtained by extrapolating the linear Gain−V relation to Gain = 1. We identified the latter with the turn-off voltage, Voff, the voltage at which the Geiger discharge stops. The method of the minimum of the Inverse Logarithmic Derivative, ILD, as well as a fit of the I−V data assuming a quadratic dependence of ILD on V are used to determine Vbd. For the non-irradiated and the SiPMs irradiated to low fluences, the ILD method gives a Vbd value, which is systematically higher by about 100 mV. For the fluence dependence of Vbd it is found that it is constant up to 5 10^12 cm-2 and then increases. The I−V data are also used to estimate the dependence of the Dark Count Rate, DCR, on voltage, fluence and temperature. The DCR increases by up to seven orders of magnitude with neutron irradiation. Using the concept of Pixel Occupancy, eta, the reduction with voltage of the dynamic range of the SiPM as a photo-detector is estimated. At the highest fluences the occupancy at low excess voltage is so high, that the SiPM is expected not be any more a useful photodetector.
By integrating the current-transients without illumination pulse-area spectra for gate widths of 15, 30, 45, 60 and 75 ns are obtained and their moments determined. From the variances the DCR as a function of excess voltage, neutron fluence and temperature is derived. The results are compared to the DCR results discussed above. An analysis of the uncertainty related to the difference of Vbd and Voff for the gain and of the excess noise factor, which could not be determined at high DCR, is presented.
From the current transients of the SiPM illuminated by a blue pulsed LED with a pulse width of ≈3 ns, the performance of the SiPMs as light detectors as a function of neutron fluence and temperature is determined. The number of photons, which was chosen to give about 100 Geiger discharges per pulse, is sufficiently high, so that signal and dark pulses are well separated. The results are compared to the results of the occupancy method discussed above.
The main emphasis of the talk is on the methods developed for characterizing the properties and performance of radiation-damaged SiPMs.

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