PROCEEDINGS OF SCIENCE

Characterization and X-Ray damage of Silicon Photomultipliers

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For Hamamatsu silicon-photomultipliers (SiPM) S10362-11-050P before and after irradiation to 200 Gy, 20 kGy, 2 MGy and 20 MGy, forward current–voltage, reverse current–voltage, capacitance/conductance–voltage, capacitance/conductance–frequency, pulse shape and pulse height measurements below and above the breakdown voltage were performed. The data were analyzed using an electrical model of the SiPM which allowed determining characteristic parameters like pixel capacitance, quench resistor and quench capacitance, parasitic resistance, and breakdown voltage in different ways, and studying their dependence on X-ray dose. In addition, the doping profile and the electric field distribution in the SiPM have been determined. It is found that the electrical model provides a consistent description of the data.

The main changes with X-ray dose are a decrease of the parasitic resistance, and an increase in dark current due to current generation at the Si–SiO$_2$ interface. Whereas for dose values of 20 kGy and below the surface generation current hardly affects the properties of the SiPM above the breakdown voltage, it gets amplified for dose values above 20 kGy resulting in a significant increase in dark-count rate. Apart from this effect, the performance of the Hamamatsu SiPM as high-gain photodetector is hardly affected by X-ray radiation up to a dose of 20 MGy.

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1. Introduction

A SiPM consists of a matrix of avalanche photodiodes connected in parallel and operated above the breakdown voltage in Geiger mode. Relevant parameters which characterize the SiPM performance are: signal shape, gain, dark-count rate, cross talk, afterpulse rate, breakdown voltage, and their dependencies on voltage and temperature.

We determine the parameters of the Hamamatsu SiPMs using measurements below and above breakdown voltage, and present the results for doses of 0, 200 Gy, 20 kGy, 2 MGy, and 20 MGy of X-ray irradiation without applied bias voltage. Details of the measurements can be found in Ref [2]. As we anticipate that X-ray radiation damage depends on the details of the SiPM design, we plan to extend these studies to SiPMs from other producers.

2. X-ray radiation damage in silicon sensors

X-rays with energies below 300 keV, which is the threshold energy for the formation of defects in the silicon bulk, generate only defects in the dielectrics, at the Si–SiO_2 interface and at the interfaces between dielectrics. The effects of X-ray radiation damage are discussed in detail in Refs. [3, 4].

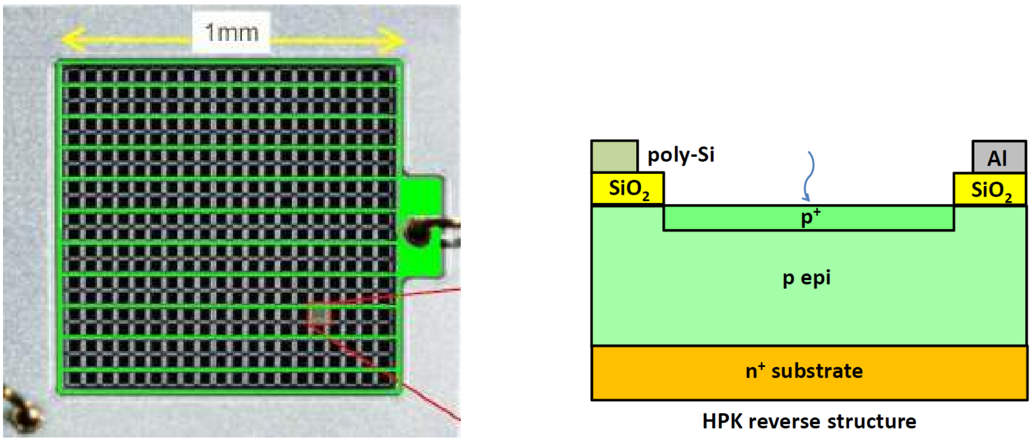
In SiO_2, X-rays produce on average one electron–hole (*eh*) pair every 18 eV of deposited energy. Depending on ionization density and electric field, a fraction of the *eh* pairs recombine. The remaining charge carriers move in the SiO_2 by diffusion and, if an electric field is present, by drift. Most electrons, due to their high mobility and relatively low trapping probability, leave the SiO_2. However holes, which move via polaron hopping, are typically captured by deep traps in the SiO_2 or at the Si–SiO_2 interface, which results in fixed positive charge states and interface traps.

The interface traps at the Si–SiO_2 interface areas generate surface currents, and therefore we expect a significant increase in dark current below the breakdown voltage. In case a fraction of the charge carriers from the surface current reaches the amplification region, an increase in dark-count rate will also occur above the breakdown voltage. This however depends on the details of the SiPM design.

3. Sensors and X-ray irradiation

Sensors of the type Hamamatsu S10362-11-050C [5] were used for the studies. They have 400 pixels of 50 µm×50 µm and a total area of 1 mm×1 mm. Fig. 1a shows an overall view of the SiPM and Fig. 1b shows a schematic cross-section. Compared to the figure given in [6], the SiO_2 layer, the Al-contact line, and the poly-Si layer of the quenching resistor have been added. From the capacitance measured above full depletion we estimate a depth of the p-epitaxial layer of about 2.3 µm. We assume that the p^+ implant is covered by an anti-reflection coating, which however should not affect the electrical properties of the SiPM.

The X-ray irradiations up to 20 kGy were performed at an X-ray tube (PW 2273/20 from PANalytical). Using a Mo target the dose rate in SiO_2 at a distance of 20 cm was approximately 0.6 Gy/s. After characterizing the SiPMs, four have been irradiated to 200 Gy and two of those later to 20 kGy. No bias has been applied to the SiPM during irradiation. The X-ray irradiations to



(a) (b)

Fig. 1: (a) Photo of the Hamamatsu S10362-11-050C taken from Ref. [1]. (b) Schematic cross-section of the Hamamatsu S10362-11-050C after Ref. [6].

2 MGy and 20 MGy were performed with X-rays of 8 keV in the P11 beam line of PETRA III with a dose rate of approximately 2 kGy/s. Two sensors were irradiated to 2 MGy, and two others to 20 MGy. All irradiations and measurements were performed at 22 to 25°C. In between irradiations and measurements the SiPMs were stored at -20°C to prevent annealing.

4. Method and results

In addition to the results presented in Ref. [2], the breakdown voltages of the SiPMs are determined using the reverse current-voltage curve in the SiPM operation region. The determined breakdown voltage is compared to the breakdown voltage measured by the gain measurement described in Ref. [2].

4.1 Gain and breakdown voltage

The SiPMs have been illuminated by a pulsed LED. The light intensity was chosen so that the average number of pixels fired per LED pulse was about 2. The output signal of the SiPM was amplified by a factor 50 using a Phillips Scientific Amplifier (Model 6954) and recorded by a CAEN charge-to-digital converter (QDC 965). The gate width was 100 ns, and the start of the SiPM signal was delayed by 20 ns relative to the start of the gate. For the absolute charge normalization we used the information from the data sheets of the different components: A gain of 50 for the amplifier and a calibration of 25 fC/channel for the QDC 965.

Fig. 2 bottom shows the pulse-area spectrum in QDC units for a non-irradiated SiPM measured at 71.5 V. The peaks of the pulse-area spectrum are individually fit by Gaussian functions, and the relation between the number of discharging pixels, n_{pix}, and integrated charge, Q_{meas}, is obtained from a straight-line fit to the mean values of the Gaussian functions from the fits. According to

$$G(V) = \frac{1}{q_0} C_{pix}(V_{op} - V_{BD}^{G}) \tag{4.1}$$

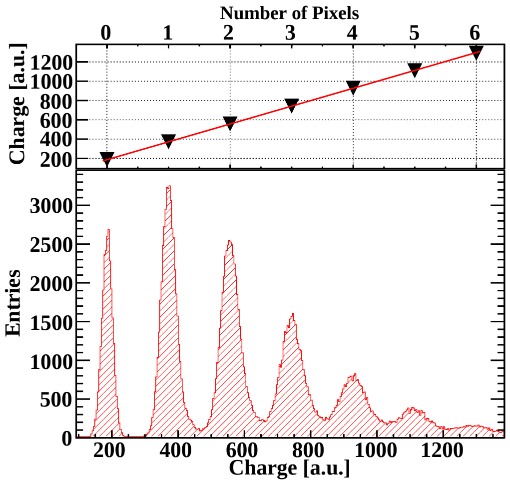


Fig. 2: Determination of the gain and breakdown voltage for the MPPC. Shown are the pulse-area spectrum in QDC units for the non-irradiated SiPM measured at 71.5 V with a fit to the spectrum for the determination of the relation between the number of discharging pixels, n_{pix}, and pulse area.

the signal from a single discharging pixel is approximately given by the product of the pixel capacitance, C_{pix}, times the excess voltage, $V_{op} - V^G_{BD}$, if the quench capacitance C_q is ignored. We thus use a straight-line fit for $G(V)$ with the slope C^G_{pix}/q_0 to determine the breakdown voltage, V^G_{BD} and the slope of the gain curve $\mathrm{d}G/\mathrm{d}V$. Here we use the superscript to represent the method that is used to determine the breakdown voltage, V_{BD}, of the device.

4.2 Reverse current and breakdown voltage

An assumption of the reverse currents' dependence on the bias voltage in the voltage region above the V^I_{BD} of the device was made. When operated in dark environment, the pixel firing due to the dark counts and their correlated noise (pixel cross talk and after-pulsing) mainly contribute to the measured current. Since the dark count rate and the cross talk probability show an approximately linear dependence on the bias voltage, and the gain of the SiPM increases linearly with the approximated excess bias voltage, we have the measured current by:

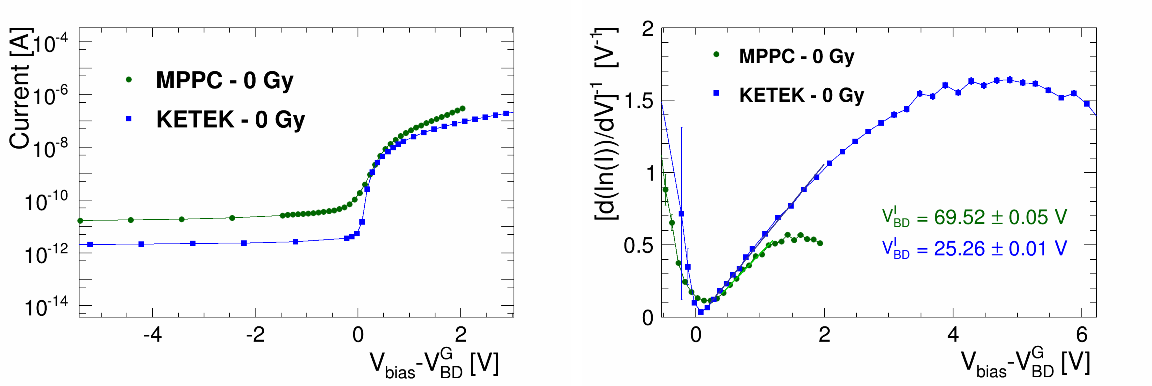
$$I = \alpha(V_{bias} - V^I_{BD})^n \tag{4.2}$$

where I is the measured current, α and n are constants which determines the shape of the reverse current-voltage curve. Therefore the reciprocal derivative of the logarithm of reverse current-voltage is:

$$[\frac{dln(I)}{dV}]^{-1} = \frac{(V - V^I_{BD})}{n} \tag{4.3}$$

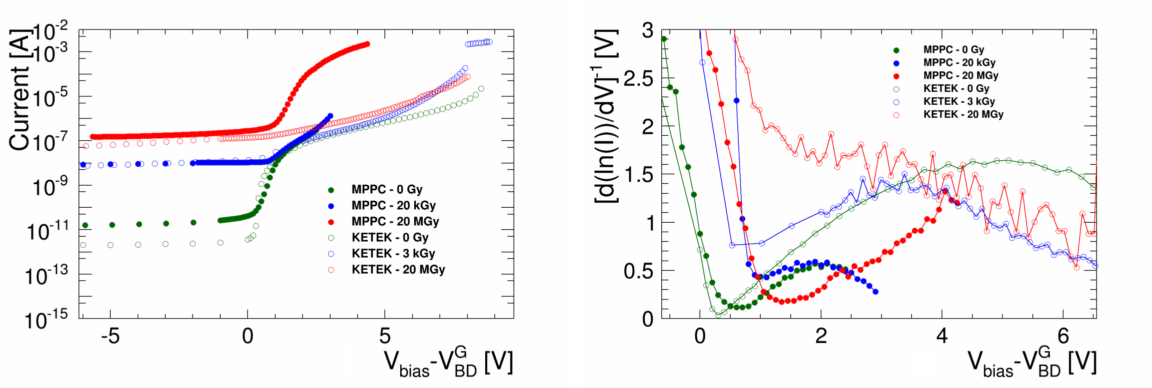
which shows a linear behavior.

A straight line is made to the inverse of the logarithmic derivative of the measured current in the SiPM's operational voltage region, and the breakdown voltage, V^I_{BD}, is obtained by the intercept of the straight line with the horizontal axis. This method is used for the MPPC before irradiation and a prototype SiPM from KETEK GmbH. The SiPM from KETEK GmbH has the pixel size of $25\ \mu\text{m}\times 25\ \mu\text{m}$ and in total 2304 pixels.



(a) (b)

Fig. 3: (a) Reverse currents of a MPPC and a SiPM from KETEK GmbH as function of voltage before X-ray irradiation. The applied voltage is rescaled to the breakdown voltage measured by the charge area spectrum method shown in Ref. [2]. (b) The reciprocal logarithmic derivative curves of the reverse current voltage measurement. The V_{BD} written in the frame are obtained by the linear extrapolating the curve in the SiPM operational region to zero of the vertical axis.



(a) (b)

Fig. 4: (a) Reverse currents of a MPPC and a SiPM from KETEK GmbH before and after X-ray irradiation of different doses. The applied voltage is rescaled to the breakdown voltage measured by the gain versus voltage method. (b) The reciprocal logarithmic derivative curves of the reverse current voltage measurement.

Fig. 3a shows the reverse current as a function of voltage of the two tested SiPMs before irradiation. The x axis in Fig. 3a and 3b is the difference of bias voltage minus the breakdown voltage, V_{BD}^{G}, determined with the gain method that is described in Section 4.1. The breakdown voltage, V_{BD}^{I}, from the reverse current-voltage measurements are written in Fig. 3b. For non irradiated SiPMs, the results from both methods are shown in Table 1. They agree with each other and have comparable precision.

Table 1: Comparison of V_{BD}^{G} and V_{BD}^{I} for two SiPM samples.

	Gain-V	I-V
MPPC	69.47 ± 0.03	69.52 ± 0.05
KETEK	25.22 ± 0.01	25.26 ± 0.01

While the breakdown voltage extracted from the gain versus voltage measurement is practically unaffected by radiation, the IV curves change significantly in shape (shown in Fig. 4), to the point that the linear approximation of Eq. 4.3 does not hold any longer. Therefore, we have used in Ref. [2] the more conventional definition of V_{BD} and initiated further studies to understand in depth the behavior of the sensor current after irradiation.

5. Conclusion

A detailed characterization of the SiPM MPPC S10362-11-050C from Hamamatsu below and above breakdown voltage, as well as for forward biasing, before and after irradiation with X-ray doses to 200 Gy, 20 kGy, 2 MGy and 20 MGy without applied voltage are presented in Ref. [2]. In this manuscript, we present a new method to determine the breakdown voltage from the reverse current-voltage characteristic. The breakdown voltages extracted for non-irradiated sensors using both methods are consistent and have comparable errors. Further studies are required to investigate if the method works for different types of SiPMs and to better understand in depth the behavior of the sensor current after X-ray and hadron irradiations.

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