Extraction of activation energies from temperature dependence of dark currents of SiPM

E Engelmann[1], S Vinogradov[2,5], E Popova[3], F Wiest[4], P Iskra[4], W Gebauer[1], S Loebner[1], T Ganka[4], C Dietzinger[4], R Fojt[4] and W Hansch[1]

[1] Universitaet der Bundeswehr Muenchen, Department of Electrical Engineering and Information Technology, Institute for Physics, Werner-Heisenberg-Weg 39, Neubiberg, 85577, Germany
[2] Cockcroft Institute, University of Liverpool, 4 Keckwick Lane, Daresbury, Warrington WA4 4AD, United Kingdom
[3] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia
[4] KETEK GmbH, Hoferstrasse 3, Munich, 81737, Germany
[5] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Leninskij Prospekt 53, Moscow, 119991, Russia

E-mail: `eugen.engelmann@unibw.de`

Abstract. Despite several advantages of Silicon Photomultipliers (SiPM) over Photomultiplier Tubes (PMT) like the increased photon detection efficiency (PDE), the compact design and the insensitivity to magnetic fields, the dark count rate (DCR) of SiPM is still a large drawback. Decreasing of the SiPM dark count rate has become a modern task, which could lead to an enormous enhancement of the application range of this promising photo-detector. The main goal of this work is to gain initial information on the dark generation and identify the dominating contributions to dark currents. The chosen approach to fulfill this task is to extract characteristic activation energies of the contributing mechanisms from temperature dependent investigations of dark currents and DCR. Since conventional methods are not suited for a precise analysis of activation energies, a new method has to be developed. In this paper, first steps towards the development of a reliable method for the analysis of dark currents and dark events are presented.

1. Introduction

The dark count rate (DCR) of the Silicon Photomultiplier (SiPM) is still a limiting factor for the extension of its application range and requires a significant reduction. In order to achieve this requirement, a distinction of contributions determining the DCR is needed to be able to identify the dominating mechanisms. As reported in [1, 3, 4, 5] the extraction of characteristic activation energies from the temperature dependence of the dark current is able to provide information on the dominating mechanisms. Unfortunately these methods are not suited for a precise determination of the needed energy levels, since the investigated dark currents are determined by a mixture of effects depending on voltage on the one hand (e.g. generation current, electric field effects) and overvoltage on the other hand (e.g. gain, crosstalk, afterpulsing). In this paper, we propose a new method to separate the mentioned effects using the responsivity of the detector as an appropriate reference for the measured dark current. This approach allows us

to generate a field-independent expression for the initial amount of charge carriers provided to or generated inside the multiplication region I_{ini} (see equation 2). From the Arrhenius plot of I_{ini}, characteristic activation energies can be extracted in an accurate way in order to identify the dominating mechanisms. In this work, the investigations were performed on a PM3350T device provided by KETEK GmbH. The device had an area of $3 \times 3\ mm^2$ with a micro-cell edge size of $50\mu m$ and implemented optical trenches (see http://www.ketek.net/products/sipm/pm3350/).

2. Conventional method

Using the conventional method for the extraction of activation energies [1], dark currents at a fixed voltage as well as dark currents at a fixed overvoltage were investigated as a function of $1/kT$ (Arrhenius plot). The breakdown voltage of the investigated SiPM was $27.3V$ at $20°C$. The results are shown in figure 1 and 2, respectively. In both plots two clearly distinguishable
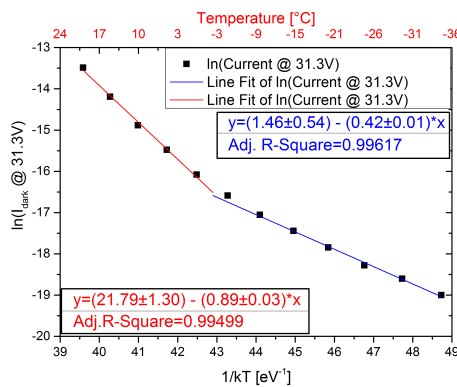

Figure 1. In this figure the Arrhenius plot of dark currents at a fixed voltage of 31.3V is shown.(Error bars are within the data points.)
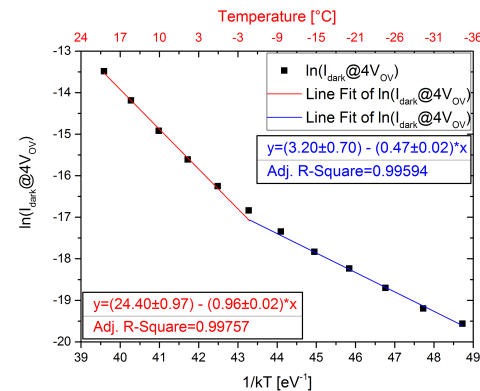

Figure 2. In this figure the Arrhenius plot of dark currents at a fixed overvoltage of 4V is shown.(Error bars are within the data points.)

activation energies can be observed. This result was interpreted as the existence of two mechanisms, dominating in the lower (T<-3°C) and higher (T>-3°C) temperature range, respectively. Despite the qualitative similarities of both plots, the quantitative activation energies differ for both temperature ranges. The extracted energies for the fixed overvoltage case ($V_{OV} = 4V$) are $(0.96 \pm 0.02)eV$ and $(0.47 \pm 0.02)eV$. For the Arrhenius plot at a fixed voltage of 31.3V the energies amount to $(0.89\pm0.03)eV$ and $(0.42\pm0.01)eV$. Since the underlying effects which lead to dark current or dark count rate depend on the applied electric field as well as on the gain and efficiency of the Geiger discharge development (crosstalk, afterpulsing) of the detector, the SiPM response is dependent on the applied voltage and overvoltage simultaneously. For this reason, the conventional method does not provide reliable results for a sophisticated analysis of activation energies.

3. Proposed method

In order to realize a separation of voltage dependent high-field effects and overvoltage dependent gain and efficiency effects of the detector, we propose an investigation method which is based on two independent measurements of the SiPM response. The first measurement is performed under illuminated conditions (here for $\lambda = 600nm$), the second one under dark conditions.

3.1. First approach

In the first step of the method, the responsivity (R) of the SiPM was defined for every temperature as shown in equation (1). Here I_{ph} is the photo response of the SiPM. The assumption was made, that the responsivity of the device is equal for photon-induced charge carriers (R_{ph}) and charge carriers originating from dark generation (R_{dark}). In figure 3 the responsivity and the dark current of the investigated device are shown at 20°C. Further the dark response of the detector (I_{dark}) can be expressed in terms of the responsivity R_{ph}, the initial dark component before multiplication I_{ini} and a component I_{not_gained}, which is not affected by the responsivity, as shown in equation (2). Here I_{ini} describes the initial amount of generated charge carriers inside or provided to the high-field region before multiplication, I_{not_gained} accounts for charge carriers that do not pass the high-field region and are thus not multiplied.

$$R_{dark}(V_{OV}) \approx R_{ph}(V_{OV}) = \frac{I_{ph}(V_{OV})}{I_{ph}(V_0)} \qquad (1)$$

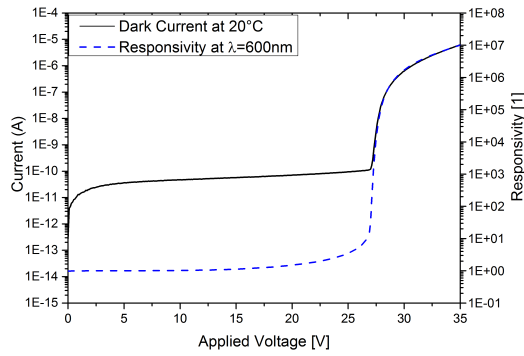$$I_{dark}(V,T) = I_{ini}(V,T) \cdot R_{ph}(V_{OV}) + I_{not\_gained}(V,T) \qquad (2)$$

Figure 3. In this figure the responsivity at $\lambda = 600nm$ and I_{dark} at 20°C is shown. (Uncertainties are within the data points.)

Applying equation (2) to dark currents, the initial current component (I_{ini}) can be determined as shown in figure 4 (solid line). The assumption was made, that the dark current consists of two contributing components. The first component was associated with surface currents or peripheral currents which flow at low field conditions (I_{not_gained}). The dominating part of these currents does not reach the high-field region of the device and thus is not multiplied. I_{not_gained} was assumed to increase with increasing depletion width and was modelled with a square root dependence on the applied voltage. The second contribution to the total dark current is a fraction δ of I_{not_gained} which does reach the multiplication region. Modelling the multiplied component I_{ini}, δ was chosen such that the breakdown point (see red circle in figure 4) was matched. The total current is then given by equation (3). The reconstructed currents for three temperatures are shown in figure 5. The experimental data is underestimated by the reconstructed dark currents at higher voltage regions. This result was expected, since no high-field effects were taken into account so far.

$$I_{dark} = (1 - \delta)\, I_{not\_gained} + \delta \cdot I_{not\_gained} \cdot R_{ph} \qquad (3)$$

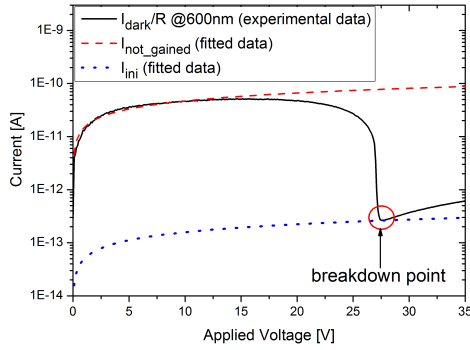$$I_{ini} = \delta \cdot I_{not\_gained} \qquad (4)$$

Figure 4. In this figure the determined initial component of the dark current (I_{ini}) as described in equation (2) is shown. (Experimental uncertainties are within the data points.)
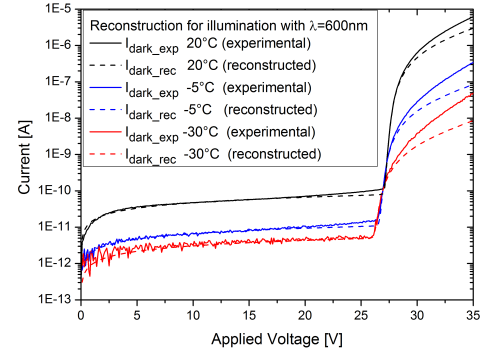
Figure 5. In this figure the reconstructed currents using the model described in equation (3) are shown for three temperatures. (Experimental uncertainties are within the data points.)

3.2. Second approach

In a second approach of the dark current reconstruction an additional parameter (F_{field}) was implemented, which should account for the electric field contributions. The total current was then modelled using equation (5). In order to investigate the multiplied component of the dark current, the difference between the experimental data and the fitted I_{not_gained} was build. The resulting function I_{diff} could be described with a second order polynomial fit in R_{ph}. The applied fit function is shown in equation (6). This approach provides a voltage independent expression for dark generation (I_{ini}) to be investigated in an Arrhenius plot.

$$I_{dark}(T, V, V_{OV}) = (1 - \delta) \, I_{not\_gained}(V, T) + I_{ini}(T) \cdot R_{ph}(V_{OV}) \cdot F_{field}(V) \tag{5}$$

$$I_{diff} = I_{ini} \cdot R_{ph} \cdot F_{field} = I_{ini} \cdot R_{ph} \left(1 + \frac{R_{ph}}{R_{eff}} \right) \tag{6}$$

4. Results

Investigating the parameter I_{ini} as a function of $1/kT$, two activation energies could be observed and attributed to the full bandgap energy (E_g) for T>-3°C and the half bandgap energy ($E_g/2$) for T<-3°C (see figure 6). Using equations (7) (here shown for electrons) and (8) as described in [2], a dominating diffusion current for T>-3°C and a dominating generation current for T<-3°C could be identified.

$$I_{diffusion}^{electron} = q \sqrt{\frac{D_n}{\tau_n}} \frac{n_i^2}{N_A} \sim T^{\frac{\gamma}{2}} \left[T^3 \exp\left(-\frac{E_g}{kT} \right) \right] \tag{7}$$

$$I_{generation} = q \frac{n_i W_D}{\tau_g} \sim \exp\left(-\frac{E_g}{2kT} \right) \tag{8}$$
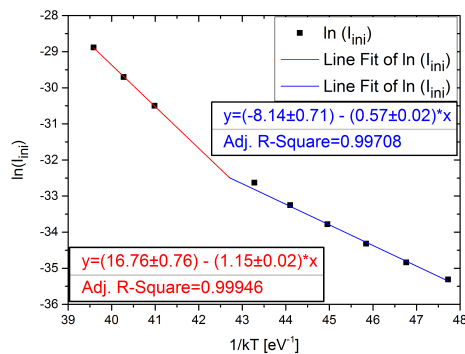
Figure 6. In this figure the Arrhenius plot of I_{ini} is shown. (Error bars are within the data points.)
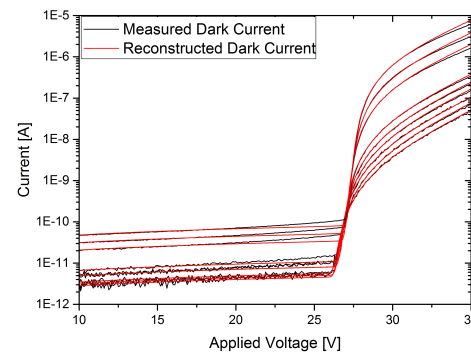

Figure 7. In this figure the reconstructed currents using equation 5 are shown. (Error bars are within the data points.)

Using the second approach, the constructed dark currents reproduce the experimental data to a more precise level (see figure 7). For higher temperatures ($I_{diffusion}$ is dominating), the reconstructed currents overestimate the experimental data in high overvoltage regimes. The observed divergence is owed to the electric field correction F_{field}. The correction must not be applied to the diffusion component of the dark current, since the electric field dependence of $I_{diffusion}$ can be neglected, as reported in [3]. Since the correction was applied to the total multiplied current, it was expected to observe an overestimation in high overvoltage regimes, especially at temperature, for which the diffusion component is dominating.

5. Conclusion

In this work, a first step towards a reliable investigation method of dark current contributions based on the responsivity of the SiPM was presented. The developed model for dark currents could reproduce the experimental data to a sufficiently precise level allowing the separation of field-enhanced effects from dark generation components. In combination with temperature dependent measurements, it was possible to identify a diffusion current to be the dominant contribution to dark events at temperatures T>-3°C, for the investigated SiPM.

References

[1] Pagano R *et al.* 2012 Dark Current in Silicon Photomultiplier Pixels: Data and Model *IEEE Trans. Electron. Dev.* **59**(9) 2410-16

[2] Sze S M and NG K K 2007 *Physics of Semiconductor Devices* (John Wiley and Sons, Inc.)

[3] Poyai A *et al.* 2001 Improved extraction of the activation energy of the leakage current in silicon p-n junction diodes *Appl. Phys. Lett.* **78** 1997-9

[4] Auffray E *et al.* 2015 Characterization studies of Silicon Photomultipliers and crystal matrices for a novel time of flight PET detector *arXiv*:1501.04233v1 [physics.ins-det]

[5] Dinu N *et al.* 2010 Temperature and Bias Voltage Dependence of the MPPC Detectors *IEEE Nuclear Science Symposium Conference Record (NSS/MIC)* pp 215-9 (DOI: 10.1109/NSSMIC.2010.5873750)