Chapter 1

Introduction

This thesis has two major points of attention. The first one is the development of innovative characterization methods for the identification and evaluation of the physical effect which underlie the generation of dark pulses in Silicon Photomultipliers (SiPMs). The second one is the reduction of the dark count rate in SiPMs by the suppression of these effects.
This chapter introduces the research which is presented in this thesis. In section 1.1, the general idea of single-photon detectors is briefly introduced. Section 1.2 treats the properties of state of the art Silicon Photomultipliers and gives an overview of their field of applications. The motivation of this work and its objectives are presented in section 1.3. In section 1.4 the structure of this thesis is summarized.

1.1 Single photon detection

In general, the setup for the detection of optical signals consists of three major parts: (a) the sensor for the detection of the incoming light, (b) the data acquisition unit for the amplification and readout of the sensor output signal, and (c) the data processing unit for the analysis of the acquired signals. Each of these parts introduces noise to the system which leads to a deterioration of the light detection. If the output signal of the sensor is amplified with a sufficiently large gain, the noise which is introduced by the data processing unit can be neglected. To overcome the limitations imposed by the noise of the electronic amplification circuit on the minimum detectable signal level, optical sensors with an internal amplification are used. Examples of such sensors, which are capable of the detection of single photons, are Photomultiplier Tubes (PMTs), Micro-Channel Plates (MCPs), Hybrid Photon Detectors (HPDs), Single-Photon Avalanche Diodes (SPADs) and Silicon Photomultipliers (SiPMs).

Despite the fundamental differences of the mentioned photon counters, they all share the same general operation principle which is based on the effect of charge-carrier multiplication. The impinging photon is absorbed inside an active volume and generates secondary charge carriers. These charge carriers are accelerated inside the high electric field which is applied across the active volume and gain enough energy to generate further charge carriers along their path, and so on. This multiplication chain leads to an internal gain of the order of 10^5 to 10^7, depending on the photon counter and the operation conditions. For a detailed description of the respective detector principles, the following literature is recommended [1], [2], [3], [4].

1.2 Silicon Photomultiplier

The Silicon Photomultiplier was proposed in the late 1980s by the Russian scientists Z. Sadygov and V. Golovin as an array of Geiger-Mode Avalanche Photodiodes connected in parallel [5], [6]. After a significant progress in the development of SiPMs over the last three decades, they have become promising candidates for a large number of applications which are distributed over a wide range of disciplines like high-energy physics, astro-particle physics, biophotonics, medical applications, dark matter search and many others.

State of the art SiPMs provide a peak photon detection efficiency (PDE) of $40 - 60$ % at a wavelength of $\lambda = 420$ nm. At 550 nm still 60 % of the peak value is achieved [7]. This makes them a suitable candidate for high energy astro-particle physics experiments like MAGIC or EUSO [8]. The application of classical PMTs, which provide a peak PDE of $25 - 35$ % for wavelengths around 400 nm [9], enforces serious limitations on the energy resolution and the accessible energy threshold [10].

A further advantage of SiPMs is, that they can be easily operated at cryogenic temperatures in dark matter search experiments like GERDA [11] or nEXO [12]. In these experiments, SiPMs are used for the detection of the scintillation light of cryogenic noble gases like liquid argon or liquid xenon, which emit in the vacuum ultraviolet (VUV) range ($\lambda = 128$ nm for argon and $\lambda = 175$ nm for xenon). For $\lambda = 128$ nm, state of the art SiPMs with a pitch size of 50 μm show a PDE of approximately 8 % [13]. For $\lambda = 175$ nm, the PDE increases to approximately 15 % [14]. This allows for a direct detection of the scintillation light as done in [12]. The high internal gain of 10^5 to 10^7 allows for the transmission of the output signal over several meters, without amplification. Hence, the operation of a near-detector preamplifier in the cryogenic liquid is not necessary. For this kind of experiments, SiPMs have serious advantages over traditional PMTs. The low operation voltage of $25 - 70$ V of SiPMs compared to $1 - 3$ kV for PMTs, excludes spark breakdowns in noble gas atmosphere, reduces the total power consumption and simplifies the operation of the detector. The small size of SiPMs and the advanced fabrication process of silicon, allows for low concentrations of radioactive impurities which are not achieved in traditional PMTs [15].

The compactness of SiPMs allows for the construction of detectors with a high degree of granularity [16], which is one of its main advantages over traditional PMTs or HPDs for the application in high energy physics (HEP) calorimeters like the CMS HCAL [17]. Since the calorimeters are operated inside a spectrometer magnet, the insensitivity of the SiPMs to magnetic fields is also beneficial for applications in such HEP detectors [18]. One of the weak-points of the SiPMs is the temperature dependence of key parameters like the breakdown voltage and the dark count rate. For the operation of a large number of SiPMs, a control system for parameter monitoring and temperature stabilization is mandatory [19], [20]. In HEP detectors, the SiPMs are operated in radiation-hostile environments. For the CMS HCAL phase I upgrade the accumulated dose of neutrons with energies larger than 100 keV is expected to be approximately $1 - 2 \cdot 10^{12}$ cm^{-2} of 1 MeV equivalent neutrons in the SiPM readout region. For such high irradiation doses, the dark count rate of the SiPMs is expected to increase by several orders of magnitude due to the introduced crystal damages [21]. After a micro-cell has fired, it is not able to detect a photon during its recovery process. The increased dark carrier generation rate after irradiation hence leads to saturation effects and losses in PDE, because the average number of recovering micro-cells at a certain time increases with the dark count rate. In order to increase the radiation hardness of SiPMs, a high dynamic range (large number of micro-cells) and a fast recovery time (small micro-cell capacity) are mandatory. State of the art SiPMs with the highest micro-cell density of 20530 cells/mm^2 and a micro-cell pitch of 7.5 μm were presented by [22]. The recovery time of this SiPM type amounts to approximately 4 ns and the achieved PDE is larger than 20 % at $\lambda = 515$ nm. With a micro-cell pitch of 12.5 μm, a PDE of approximately 30 % at $\lambda = 515$ nm was achieved with a micro-cell density of 7500 cells/mm^2 and a recovery time of approximately 10 ns.

Smaller micro-cells show a faster avalanche buildup time and a faster signal rise time. For this reason, SiPMs with small micro-cells are beneficial for applications which require a high single-photon time resolution [23]. However, the disadvantage of smaller micro-cells is a lower fill factor and hence a lower photon detection efficiency. In medical applications, the "Time-of-Flight Positron Emission Tomography" (TOF-PET) detector-systems impose strong requirements on the SiPM time resolution. TOF-PET systems measure the difference in arrival times of 511 keV annihilation photons at the outer detector ring using a scintillator readout. Here, one of the figures of merit is the coincidence time resolution (CTR) of the detector system, which strongly depends on the properties of the scintillator and the photon detector. CTR values of 205 ps FWHM were reported for a 8x8 LYSO array with a pixel size of 4x4x22 mm^2 matching a SiPM array with an active area of 4x4 mm^2 per pixel [24]. To achieve a high CTR in TOF-PET, the detector has to trigger on the first arriving photons from the scintillation pulse. For this reason, the pulse discriminator threshold must be set at the single photoelectron level. At such low threshold levels, the dark pulses of the SiPM degrade the signal to noise ratio of the detector system and consequently the time resolution [25]. For the selection of events associated with the 511 keV, a good energy resolution is mandatory. As reported in [24], both the coincidence time resolution and the energy resolution improve with a decreasing rate of dark pulses.

It was shown that SiPMs are also suitable for the application in a variety of optical biosensors, where the challenge is to detect small photo-signals while maintaining high contrast [26]. In applications like "Fluorescence Correlation Spectroscopy" (FCS) [27] or "Fluorescence Lifetime Imaging" (FLIM) [28], photon detectors with a high time resolution are required, which favors the SiPMs. For applications which use bio-luminescence, additionally the detection of low emission intensities with a high signal to noise ratio is mandatory. Since the minimum detectable light intensity scales with the square root of the dark noise, the relatively high dark count rate of SiPMs with respect to PMTs is a limiting factor for high contrast imaging, especially at room temperature [29]. The high dark count rate also imposes a restriction on the maximum size of the active area of SiPMs. This problem is often solved by coupling the photon detector to optical fibers or micro-lenses, which increases the complexity of the detector system [30]. However, the high dynamic range of SiPMs provides a better linearity over a much broader range of light intensities than PMTs [31]. Further, its compactness, robustness and immunity to damage from light overexposure makes the SiPM a well suited candidate for the realization of compact systems for portable applications.

1.3 Motivation and objectives

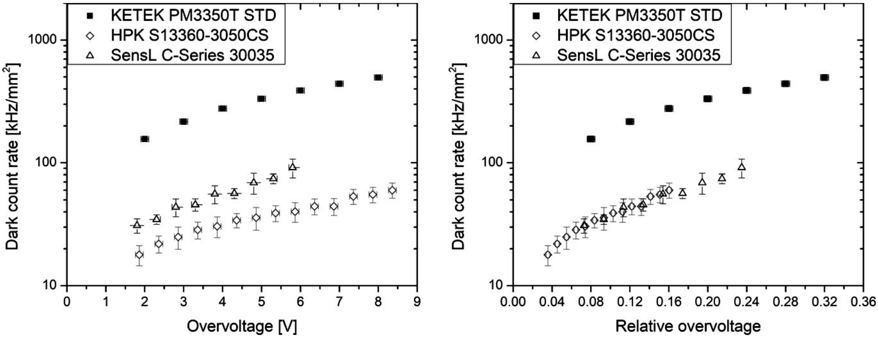
The dark count rate represents the intrinsic noise limit of the Silicon Photomultiplier and restricts the performance of this photon detector in many applications.

The creation of charge carriers at dark conditions may occur by a variety of physical mechanisms. The ratio of these mechanisms may vary, depending on the SiPM design, fabrication technology and operation conditions. For this reason, there is no general solution providing a low dark count rate for every SiPM technology. Every developer has to individually identify the mechanisms which are dominating the dark count rate of the respective SiPM. The fact that the output signal of the SiPM does not provide any spatial information on its origin makes the separation of the contributing mechanisms even more challenging.

Therefore, an important objective of the research presented in this thesis is to develop suitable methods for the investigation of physical mechanisms which determine the dark count rate of Silicon Photomultipliers.

Over the last years, several producers achieved a reduction of the dark count rate to a level of 30 to 100 kHz/mm^2. On the contrary, the KETEK SiPMs still show a dark count rate which is approximately one order of magnitude higher with respect to the state of the art devices (see figures 1.1(a) and 1.1(b)). For this reason, the second goal of this research is to make the KETEK SiPM a competitive photon detector by finding a way to suppress the mechanisms which are dominating its dark count rate.

In applications, in which the SiPMs are operated in radiation-hostile environments, the dark count rate is the parameter which degrades the fastest due to the generated defects in the silicon crystal. One of the requirements to SiPMs in these applications is to provide a dark count rate, which increases as slowly as possible with the accumulated irradiation dose, rather than being initially low. The third goal of this thesis is to contribute to the development of the radiation hardness of Silicon Photomultipliers by evaluating the dark count rate of point and cluster defects generated during the irradiation with ^{60}Co γ-rays and with thermal neutrons.



(a) DCR vs. ΔV (b) DCR vs. ΔV_{rel}

Figure 1.1: Comparison of the dark count rate of SiPMs from different producers at $T = 21$ °C.

1.4 Organization of this thesis

This thesis describes the research that was done in order to understand the origin of dark pulses in KETEK SiPMs and find suited solutions for their suppression. The thesis is divided into 9 chapters, of which this introduction is the first.

The **second chapter** treats the fundamentals of Silicon Photomultipliers. This chapter begins with a review of the operation principle of the SiPM, based on its equivalent circuit. In the second part of this chapter, the two main physical processes of impact ionization and avalanche multiplication are presented and their influence on the photon detection efficiency of the SiPM is discussed. The last part reviews the physical mechanisms which are potentially contributing to the noise of the SiPM.

In the **third chapter**, the experimental methods used for the determination of selected SiPM parameters are presented. In the first part of this chapter, the experimental setup is described on which all other setups used in this work are based. Furthermore, the developed algorithm for the signal processing and pulse detection is introduced. The second part of this chapter is focused on the determination of the SiPM parameters which are important for the line of argument in this thesis. Special attention is paid to the temperature dependence of these parameters. The last part of chapter three summarizes the SiPMs which were used in the presented research.

Chapter four discusses the identification of the diffusion current as the strongest contributor to the generation of dark pulses in KETEK SiPMs. The temperature dependence of the dark current of the SiPMs is used as an indicator of physical processes. The activation energies of these processes are extracted from the Arrhenius plots of the dark current. In the first part of this chapter, the conventional method for the extraction of the activation energies is applied and its drawbacks are discussed. In the second part of this chapter, a novel method is presented which was developed in the course of this project in order to overcome these drawbacks and improve the confidence level of the obtained results.

In **chapter five**, the elaborated solution for the suppression of the dominating diffusion current in KETEK SiPMs is presented. It is based on the application of an electric potential to the substrate of the photon detector which counteracts the diffusion of charge carriers.

Chapter six presents a method for the spatially resolved characterization of the dark count rate of Silicon Photomultipliers. The method is based on the idea of mapping the light intensity, which is emitted by the effect of hot carrier luminescence during the avalanche breakdowns of micro-cells. In the first part of this chapter, the existence of regions with an enhanced dark count rate is discussed and the contribution of these hotspots to the total dark count rate of KETEK SiPMs is experimentally determined. In the second part of this chapter, the areas in which the substrate potential has an impact on the dark count rate are identified and the achieved suppression of dark pulses is evaluated in these areas. The last part of this chapter presents an approach for the generation of activation energy maps for a spatially resolved characterization of physical mechanisms which contribute to the dark count rate of SiPMs. Using this approach, the contribution of the remaining diffusion current to the dark count rate of KETEK SiPMs is evaluated. Furthermore, the hotspots are identified as crystal defects which are introduced by the phosphorus implantation in the fabrication process.

Chapter seven treats the optimization of the phosphorus implantation parameters, aiming for a reduced contribution of hotspots to the dark count rate of KETEK SiPMs. The chapter begins with the simulation of the implantation defects for two distinct implantation energies. The simulation results are confirmed experimentally in the second part of this chapter and SiPMs with a further suppressed dark count rate are presented. In the last part of this chapter, the variation of the hotspot density and the variation of the dark count rate is investigated.

In **chapter eight**, the degradation of KETEK SiPMs due to radiation damages is characterized. The impact of the irradiation with ^{60}Co γ-rays and with thermal neutrons is evaluated. Additionally, the dark count rate which is generated by point defects is compared with the one generated by cluster defects. This chapter introduces an interesting and important field of research and motivates further projects headed in this direction.

Finally, **chapter nine** summarizes the results of the research which is presented in this thesis and gives an outlook on possible future research projects.

Chapter 2

Fundamentals

In this chapter, the fundamental physical processes are reviewed on which the operation characteristics of the SiPM are based. The chapter is divided in three main parts.
In the first part (section 2.1), the operation principle of the SiPM is presented and the equivalent circuit is discussed.
The second part of this chapter (sections 2.2 - 2.4) reviews the fundamental processes of impact ionization and avalanche multiplication. Their influence on the most crucial SiPM parameter, the photon detection efficiency, is discussed.
In the third part of this chapter (section 2.5 - 2.8), the physical origins of dark pulses, optical crosstalk and afterpulsing are presented. These processes are responsible for the generation of false pulses during the operation of the SiPM and hence deteriorate the detection of incoming photons.

2.1 Operation principle of the SiPM

A Silicon Photomultiplier is a semiconductor device that provides the ability to detect single photons with a high gain of the order of 10^5 to 10^7. The device consists of an array of avalanche photodiodes (APD) connected in parallel and operated above their breakdown voltage (V_{BD}), in Geiger-Mode (GM-APD). In this work, the individual GM-APDs are also referred to as micro-cells of the SiPM. A sketch of a GM-APD is shown in figure 2.1. It consists of p-doped and n-doped silicon layers. The layers can be generated by implantation or diffusion of dopants into the silicon crystal. Also epitaxial growth techniques are used. At the junction of these layers (pn-junction) a high internal electric field is build up, when the device is operated at reverse bias conditions. If an electron-hole pair (e-h pair) is generated inside the high-field region of the GM-APD, the electron is dragged towards the n-contact (cathode), while the hole is dragged towards the p-contact (anode).

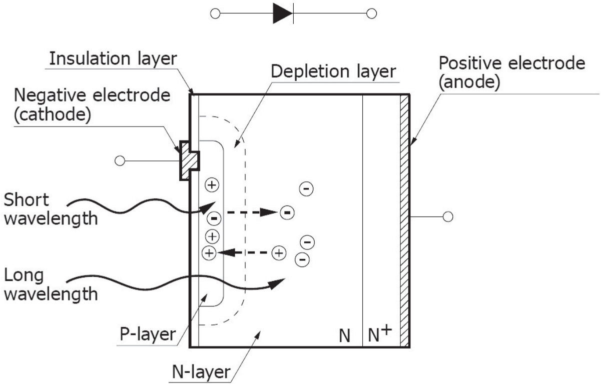


Figure 2.1: Sketch of a Geiger-Mode avalanche photodiode (GM-APD). Taken from [1].

If the electric field exceeds a certain threshold, charge carriers are able to initiate an avalanche breakdown by the mechanisms of impact ionization. As a consequence, a breakdown current is flowing, which is large enough to be detected (see sections 2.2 and 2.3).
In a GM-APD, the applied electric field strength is sufficiently high for electrons and holes to impact ionize. For this reason, the charge carrier avalanche is self sustaining and must be quenched by reducing the voltage across the diode below the breakdown voltage, after the detection of a breakdown. For the SiPMs investigated in this work, the quenching is achieved by a voltage drop across a serial polysilicon resistor (in the following referred to as quenching resistor R_q). However, also active quenching circuits may be used.
The generation of an e-h pair may occur by the absorption of a photon with sufficient energy, which leads to the single photon detection capabilities of the SiPM. However, also e-h pairs which are not generated by photons lead to avalanche breakdowns and consequently to false signals (see section 2.5). In figure 2.2, the equivalent circuit diagram of a SiPM is shown, as proposed by [32]. The model consists of a parallel connection of N avalanche photo diodes, with one of them firing at a time. This corresponds to the case of one dark pulse without correlated pulses. The depletion region of the pn-junction is modeled by the capacitance C_d. Additionally, every micro-cell consists of a polysilicon quenching resistor R_q in parallel to the parasitic capacitance C_q. The series resistance of the micro-plasma in the avalanche is accounted for by R_d [33]. The charge released by one micro-cell during an avalanche breakdown is modeled by the current source I_{AV}. The parasitic capacitance introduced by the metal interconnects of the micro-cells is accounted for by the grid capacitance C_g.