Temperature dependent Investigations of Dark Currents of SiPM


ICPPA, 10th of October, 2015
**Goal of this work:**
- reduction of dark count rate of Silicon Photomultipliers
- gain initial information on dark generation and extract contributions to dark current

**General approach:**
- activation energies determined from T dependencies are expected to be a good indicator of physical mechanisms
- conventional methods of extraction of $E_{act}$ at fixed voltages/overvoltages may not be suitable
- effects dependent on voltage and overvoltage cannot be separated

**Proposed method:**
- independent measurements of photo- and dark-response
- separation of overvoltage dependent responsivity and voltage dependent high-field effects
- find expression for field-independent generation component
• temperature dependent investigations were performed in a range from 20°C to -30°C
• the measurements were executed on a KETEK 3x3mm² SiPM which was mounted on a Peltier element and evacuated in a TO8 module
• conventional method as proposed in R. Pagano et al.; „Dark Current in Silicon Photomultiplier Pixels: Data and Model“; IEEE Transactions on Electron Devices; Vol.59 NO. 9; 2012 is not suitable here

• $E_{\text{act}}$ can not be attributed to a certain mechanism
• dark and illuminated data was taken

• assumption of an equal responsivity $R$, for electrons originating from dark generation and photoelectrons

\[
\rho(T, V, V_{OV}) := \text{Response}
\]

\[
R(V_{OV}) := \text{Responsivity}
\]

\[
R_{dark}(V_{OV}) \approx R_{ph}(V_{OV}) = \frac{\rho_{ph}(V_{OV})}{\rho_{ph}(V_0)}
\]

\[
\rho_{dark}(T, V, V_{OV}) = \rho_{ini}(T, V) \cdot R_{ph}(V_{OV})
\]

• in general this approach is applicable for any Response $\rho$, e.g. $I_{dark}$ or DCR
Determination of $I_{not\_gained}$

$$I_{dark}(T, V, V_{OV}) = I_{not\_gained}(T, V) + I_{gained}(T) \cdot F_{high\_field}(V) \cdot R_{ph}(V_{OV})$$

![Graph showing dark current at 10°C and fit of $I_{not\_gained}$ vs applied voltage.]
\[ I_{dark}(T, V, V_{OV}) = I_{not\_gained}(T, V) + I_{gained}(T) \cdot F_{high\_field}(V) \cdot R_{ph}(V_{OV}) \]

- in order to determine the multiplied component, the difference between the measured dark current and \( I_{\text{not\_gained}} \) is investigated as a function of the responsivity

\[ I_{\text{diff}}(R_{\text{ph}}) = I_{\text{gained}} \cdot R_{\text{ph}} \left(1 + \frac{R_{\text{ph}}}{R_{\text{eff}}}\right) \]

- \( I_{\text{diff}} \) could be described with a parabolic function in good agreement in the range between \( R=0 \) to \( R=4 \times 10^6 \)

- \( I_{\text{gained}} \) represents initial charge carriers generated or provided to the multiplication region
\[ I_{\text{dark}}(T, V, V_{OV}) = I_{\text{not\_gained}}(T, V) + I_{\text{gained}}(T) \cdot F_{\text{high\_field}}(V) \cdot R_{\text{ph}}(V_{OV}) \]
- $I_{\text{gained}}$ shows two activation Energies $E_{1,\text{act}} \approx E_g$ and $E_{2,\text{act}} \approx E_g/2$
- $F_{\text{high\_field}}$ lowers the effective activation energy by $\Delta E_{\text{act}}$
- $\Delta E_{\text{act}}$ is close to expected value for Poole-Frenkel effect
Results so far

➢ the chosen model for dark current could describe the measured data to a sufficiently precise level
➢ field-enhanced effects could be separated from generation components
➢ the extracted activation energies indicate that dark currents at T>-5°C are diffusion dominated, whereas currents at T<-5°C are dominated by generation (KETEK devices)

Further investigations

➢ confirmation of model for different type of devices
➢ identification of micro-cell regions as origin for diffusion currents
➢ change technological process in order to reduce DCR
Thank you for the attention
Additional Slides
1st Approach

- analysing $I_{\text{gen}}$ consisting of a multiplied and non-multiplied component

$$I_{\text{dark}} = I_{\text{not\_gained}} + I_{\text{gained}} \cdot R_{\text{ph}}$$

$$I_{\text{not\_gained}} = I_0 \cdot \sqrt{\frac{V}{V_0}}$$

- $I_{\text{gained}}$ is assumed to be a small fraction of $I_{\text{not\_gained}}$

$$I_{\text{gained}} = \delta \cdot I_{\text{not\_gained}}$$
1st Approach - Reconstruction of Dark Current

Reconstruction for illumination with $\lambda=600\,\text{nm}$

- Dark Current $20^\circ\text{C}$
- $I_{\text{const\_tot}}$ $20^\circ\text{C}$
- Dark Current $-5^\circ\text{C}$
- $I_{\text{const\_tot}}$ $-5^\circ\text{C}$
- Dark Current $-30^\circ\text{C}$
- $I_{\text{const\_tot}}$ $-30^\circ\text{C}$

Current [A] vs. Applied Voltage [V]
• a 3x3mm² C-Series device from SensL was investigated for comparison
• only one slope could be observed in the Arrhenius plot
• $E_{\text{act}}$ of $(0.57 \pm 0.02)$ eV is attributed to generation current
• the contribution of diffusion current is expected to be suppressed for this device
Reconstruction of Dark Current

Current [A] vs. Applied Voltage [V] for measured and reconstructed dark currents at 20°C and -30°C.
• the extracted $E_{\text{act}}$ directly from $I_{\text{dark}}(T)$ and DCR (T) at a fixed overvoltage show slightly different values, but agree within the uncertainties

• $E_{\text{act}}$ from „raw“ data is an indicator for physical mechanisms

• for a precise analysis, a more advanced analysis is necessary
DCR in extended T range

![Graph showing DCR vs Temperature and 1/kT vs ln(DCR @ 3Vov)]

- Temperature [°C] range: -58 to 54
- Examination of DCR at 3Vov
- Line fit of ln(DCR) with parameters:
  - Model: y = A + B*x
  - Chi-Quadrat Reduced: 0.00345
  - Correlation R-Quadrat: 0.99926
- Values for ln(DCR @ 3Vov):
  - A: 54.54548 ± 0.54387
  - B: -1.01764 ± 0.01389

ICPPA, 10th of October, 2015
Confirmation of Model

\[ DCR = \frac{I_{\text{gain}} \cdot F_{\text{high\_field}}}{q} \]

- \( E_{\text{act}} \) extracted from DCR is a sum of field-independent \( I_{\text{gain}} \) and field-dependent \( F_{\text{high\_field}} \).

- \( DCR_{\text{measured}} \) and \( DCR_{\text{reconstr}} \) show comparable \( E_{\text{act}} \) within the uncertainties.

- This result is an indicator of the parameter fit quality.

- The measured DCR has to be additionally corrected for avalanche triggering probability.
DCR reconstruction overestimates DCR measured.

Internal generation rate of dark events is expected to be higher than DCR.

The measured DCR has to be additionally corrected for avalanche triggering probability.

\[ DCR = \frac{I_{\text{gain}} \cdot F_{\text{high field}}}{q} \]