Abstract

In the context of the LHCb upgrade, the current Inner Tracker (silicon strip) and Outer Tracker (straw tubes) will be replaced with a single technology scintillating fibre tracker. The SiPM photodetectors used for the readout need to provide a high photon detection efficiency, low optical cross-talk, dense packaging and withstand a high neutron fluence. In collaboration with CERN and an SiPM manufacturer KETEK, a second batch of prototypes was produced in 2014 to evaluate different technologies. This work was focused on the study of these devices and the evaluation of their performance. The measurements of breakdown voltage, cross-talk, dark count rate, photon detection efficiency and temperature dependence were performed and the effect of neutron radiation analysed. The results show a significant reduction of the cross-talk for the double trench implementation and a general low temperature dependence. The photon detection efficiency and the expected light yield from the scintillating fibre is at the expected level of 40-44%.
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1 Introduction

The LHCb detector [1] in its initial configuration, will continue collecting data until the second long shutdown (LS2) of the LHC. Parts of the current LHCb detector need to be changed or replaced for the LHCb Upgrade [2]. Two major changes are planned. Firstly the Level-0 hardware trigger which is limited to 1 MHz will be removed and replaced by a software trigger running at 40 MHz trigger. Secondly, the current tracking station, composed of Inner Tracker (IT) and Outer Tracker (OT) will be replaced by scintillating fibers (SciFi) readout with silicon photomultipliers (SiPMs). This upgrade is scheduled during the LS2 from mid 2018 to the end of 2019 and will allow higher luminosity and higher trigger efficiency.

This work will focus on the SiPM part of the tracker and will investigate the performance of the photon detectors from two companies, KETEK and Hamamatsu.

In order to characterise the SiPMs, a series of properties like the breakdown voltage, the cross-talk, the gain or the temperature dependence need to be measured. Neutron irradiation studies were included. In order to perform the characterisation, existing setups were modified and methods to analyse the data were developed.

2 Theory

2.1 SciFi Tracker

The SciFi Tracker uses scintillating fibres coupled to SiPM detectors. When a particle passes through a scintillating fibre, the medium will produce scintillating light [3]. The number of photon created is proportional to the distance travelled by the particle in the fibres. The scintillating photons will travel inside the fibre until they hit the cladding. The photons will then be reflected or lost depending on the angle of the photon when reaching the cladding. The photons that are not lost will travel, by reflections, through the fibre until one end. An SiPM is set at one end of the fibre to detect the light. At the other end a mirror is set to reflect the photons that went in the opposite direction. A scheme can be seen in Fig. (1)

![Figure 1: Scintillating fibre traversed by a particle.](image)

For the SciFi Tracker, the fibres are arranged in layers. Five to six layers are put one over the other. The layers are shifted from one layer to the other. The SiPM is composed
of 128 channels and each channel is composed by pixels. The SiPM channels will cover the set of layers like in Fig.(2). Note that the channels and the fibres are not aligned.

Figure 3.19: The photons produced along the trajectory of the particle are propagated to the fibre end and further to the detector. Each pixel of the detector can detect one photon and the signal proportional to the total number of pixels with signal (coloured pixels) is the signal amplitude per channel illustrated in the top part of the figure. The particle position can be calculated with a weighted mean value of the channel signal. Note that the fibres are not aligned to the detector channels and the photons can arrive at the detector outside the fibre area.

made for a low temperature soldering process. The pixel size was maximised for the latest generation of detectors to increase the PDE for the low signal, and thereby reduce hit detection inefficiency. Larger pixels allow the ratio between the dead area on the border of the pixels and the active pixel ratio to be reduced. This effect is especially important for new detectors which have so-called trenches between pixels to reduce the pixel to pixel cross-talk, as shown in Fig. 3.20. The number of pixels is 96 per channel with a pixel size of $57\times62.5\ \mu m$. Three versions with different pixel size and active area height were produced by KETEK in 2014, $60\times62.5\ \mu m$ (1.32 mm high, 88 pixels) and $60\times62.5\ \mu m$ (1.62 mm high, 104 pixels). The drawbacks of the increased pixel size are the increase of pixel to pixel cross-talk and saturation (one pixel can detect only one photon can be detected by one pixel and the resulting signal is proportional to the number of triggered pixels per channel. The position of the particle is found with a clustering algorithm.

Figure 2: Layers of fibres traversed by a particle, creating photons that are detected by the pixels of the SiPM. The triggered pixels can be seen in yellow. The signal amplitude can be seen at the top of the graph. A threshold based clustering algorithm will analyse the signal resulting per channel and will determine the position of the particle (taken from[2]).

One photon can be detected by one pixel and the resulting signal is proportional to the number of triggered pixels per channel. The position of the particle is found with a clustering algorithm.
2.2 Silicon photomultiplier

Silicon photomultipliers, called SiPMs, are photon detectors formed by avalanche photodiode (APD) pixels. These avalanche photodiodes operate in Geiger mode. The photodiodes use the photoelectric effect to convert light into electrons. These electrons will move from the valence band to the conduction band. If a strong enough electric field is applied, these electrons will ionise the material and create an avalanche of electrons producing a large current [4]. A schematic structure can be seen in Fig.(3):

![Figure 3: Structure of an SiPM, view from profile (taken from [5]). SiPMs are based on P-N junctions with a highly doped P region at the light entrance. The highly doped P region is set on the top of a low doped N region forming the avalanche zone. The bottom region of the SiPM is composed of a highly N-doped body. The quenching resistor is made of doped polysilicon strip line.](image)

This work will focus on arrays of SiPMs. These arrays consist of two dies of 64 channels making a total of 128 channels [2].

Arrays from two different producers will be looked at. First, Hamamatsu detectors will be tested and they will serve as a reference. Then KETEK detectors with new technologies will be characterised.

KETEK detector dies were directly bonded to a PCB. Note that these bonds are very fragile. A plexiglas protection is set over the KETEK detectors to reduce the risk of damage to the bonds. A hole of 6 mm diameter was made in the protection to allow the light to enter directly for the photon detection efficiency measurement. The PCB is coupled to a flexible part, called the flex, that brings the connections of each SiPM channel to one of the two connectors. These connectors are called J1 and J2. A picture of a bonded KETEK detector can be seen in Fig.(4) and in Fig.(5). Hamamatsu detectors follow the same procedure but the plexiglas protection is replaced by an epoxy layer.

2.2.1 2014 Prototype KETEK detectors

A prototype run with KETEK was bonded in early 2012 and a second in 2013. Their dimensions are similar to Hamamatsu but for optimisation, the pixel sizes were varied and the channel height was adapted for 6-layer modules. Various technologies were implemented for testing. A set of twelve wafers, each one with four chips, were available. Some of the these wafers and chips were selected; w1c2/3, w2c2/3, w3c2/3, w4c2/3, w7c2/3, w8c2/3, w9c2/3 and can be found in Tab.(1). Chip two has a pixel size of 60 µm x 62.5 µm. Chip three has bigger pixels, 82.5 µm x 62.5 µm.

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One of the new technologies developed by KETEK uses additional opaque trenches. Wafers 3, 4, 5, 7 and 11 have an additional trench around the detector. Chip two has additional trenches in the y direction, and chip three has trenches in both the x and y direction. Note that these additional trenches reduce the photo sensitive active area. The effective reduction is given by the fill factor, which is defined as:

$$ FF = \frac{\text{Active Area}}{\text{Total Area}} $$

Table 1: KETEK 2014 prototype technologies.

<table>
<thead>
<tr>
<th>Wafer Nr</th>
<th>Chip</th>
<th>Additional trench x</th>
<th>Additional trench y</th>
<th>Epitaxial Layer</th>
<th>Deep P</th>
<th>RQ</th>
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</thead>
<tbody>
<tr>
<td>W1</td>
<td>C2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5 MΩ</td>
</tr>
<tr>
<td>W1</td>
<td>C3</td>
<td></td>
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<td>0.3 MΩ</td>
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<tr>
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<td>C3</td>
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<td>C2</td>
<td></td>
<td></td>
<td>X</td>
<td>0.4 µm</td>
<td>0.5 MΩ</td>
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<tr>
<td>w7</td>
<td>C3</td>
<td></td>
<td></td>
<td>X</td>
<td>0.4 µm</td>
<td>0.5 MΩ</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>0.6 µm</td>
<td>0.5 MΩ</td>
</tr>
<tr>
<td>w8</td>
<td>C3</td>
<td></td>
<td></td>
<td></td>
<td>0.6 µm</td>
<td>0.5 MΩ</td>
</tr>
<tr>
<td>w9</td>
<td>C2</td>
<td></td>
<td></td>
<td></td>
<td>0.8 µm</td>
<td>0.5 MΩ</td>
</tr>
<tr>
<td>w9</td>
<td>C3</td>
<td></td>
<td></td>
<td></td>
<td>0.8 µm</td>
<td>0.5 MΩ</td>
</tr>
</tbody>
</table>

A. Kuonen
Characterisation of SiPM arrays

<table>
<thead>
<tr>
<th>Technology</th>
<th>Trenches size [µm]</th>
<th>Pixel Size [µm^2]</th>
<th>Active Area Size [µm^2]</th>
<th>Calculated Fill Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard trench technology</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chip 2</td>
<td>x/y = 5</td>
<td>3750</td>
<td>3162.5</td>
<td>0.843</td>
</tr>
<tr>
<td>Chip 3</td>
<td>x/y = 5</td>
<td>5156.25</td>
<td>4456.25</td>
<td>0.864</td>
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<td>Second trench technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chip 2</td>
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<td>3750</td>
<td>3052.5</td>
<td>0.814</td>
</tr>
<tr>
<td>Chip 3</td>
<td>x/y = 7</td>
<td>5156.25</td>
<td>4190.25</td>
<td>0.813</td>
</tr>
</tbody>
</table>

Table 2: Active area and Fill Factor for the different KETEK chips with the assumption that the trench produces a typical dead zone of 5 µm, and double the trench 7 µm.

A theoretical FF for the different pixel and trench versions has been calculated in Tab (2). The FF is the most important ingredient for the PDE (section 2.8) and needs to be as high as possible. A schematic of each chip can be seen in Fig.(6). Another technology under test by KETEK is the epitaxial layer present on chips 7, 8 and 9. This layer is supposed to reduce the damage due to the neutron irradiation. Various sizes of epitaxial layer were implemented. A summary of the technology used for each wafer can also be seen in Tab.(1).

![Standard Trench Technology](image1)

![Opaque Trench Technology](image2)

Figure 6: Illustration of the KETEK technology. The active area can be seen in red, the standard trench in blue and the new-opaque trenches in black. It is assumed that the single trench produces a typical dead zone of 5 µm, and the double trench 7 µm is made.

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2.3 Breakdown voltage

Some parameters are necessary in order to characterise the SiPM. The breakdown voltage \( (V_{\text{bd}}) \) is the voltage needed to start the amplification. The over-voltage is defined by:

\[
\Delta V = V_{\text{bias}} - V_{\text{bd}}
\]

with \( V_{\text{bias}} \) the tension applied. \( V_{\text{bd}} \) is typically given for 25 °C.

2.4 Cross-talk and after-pulse

During an avalanche photons are created which can travel to the neighbouring pixels and start a new avalanche there. This effect is called cross-talk. To reduce this effect, trenches are added to stop the photons created in the avalanche. Photons can also be reflected at the trench which can be one of the reasons that partial trenches around pixels are less efficient. After-pulsing is the effect that a fired pixel re-produces an avalanche after partial or fully recharged due to trapped charge carriers [7].

![Illustration of the cross-talk](image)

Figure 7: Illustration of the cross-talk. Firing pixels are shown in red. Trenches reduce the cross-talk effect.

2.5 Gain

The gain is defined as the charge \( Q \) created from one pixel when it starts an avalanche, divided by the electron charge \( e \) [6]. As the detector is a capacitor, the charge \( Q \) can be found by:

\[
Q = C \cdot \Delta V = C \cdot (V_{\text{bias}} - V_{\text{bd}})
\]

with \( V_{\text{bias}} \) the bias voltage and \( C \) the capacitance of one pixel. Larger pixels will have a higher capacitance and so a bigger gain. The gain increases linearly with the \( \Delta V \).

2.6 Temperature coefficient

SiPMs are rather sensitive to temperature because the gain is temperature dependent. The temperature rise will make the crystal lattice vibrations increase and may stop the accelerating carrier [6]. This effect will reduce the energy of the charge carrier and will make the ionisation difficult. The bias voltage needs to be adjusted to the temperature of the SiPM to keep the gain constant. For example, standard Hamamatsu detectors have a temperature dependance of -56 mV per Kelvin.
2.7  Dark count rate

Pulses can also be produced by charge carriers that are generated by thermal excitation [6]. These pulses are called dark pulses and have the same shape as photon-generated pulses. The dark count rate is the number of dark pulses per second. Detection errors are induced by these pulses.

2.8  Photon detection efficiency

The photon detection efficiency (PDE) is the ratio between the number of detected photons and the number of incident photons [6]:

\[
PDE = \frac{N_{\text{detected}}}{N_{\text{incident}}}\tag{4}
\]

It can be defined as [7]:

\[
PDE = QE \cdot FF \cdot P_b \tag{5}
\]

with:

- \(QE\) the quantum efficiency, that gives us the number of electrons or holes created as photocurrent divided by the number of incident photons.

- \(FF\) is the fill factor. SiPM contains sections that cannot detect light as the inter-pixel wiring. These are taken into account by the FF.

- \(P_b\) is the probability of the primary photoelectron to trigger the avalanche

The PDE changes with \(\Delta V\).
3 Setup and method

3.1 Breakdown voltage measurement

The setup to measure $V_{bd}$ consists of a light tight aluminum box in which the detector under test is placed. The SiPM array connectors (J1 and J2) are connected to a PCB on which the VATA64 acquisition chips are set [8]. These acquisition chips are connected to a USB module that makes the connection with the DAQ computer.

A Peltier cooling device is used to keep the detectors at a constant temperature during the complete measurement cycle. To improve the temperature homogeneity, the arrays are screwed on an aluminum holder which is placed on the Peltier. Thermal paste is put between the flex and the aluminum holder, and also between the Peltier and the holder. Note that the Peltier should only be used when the chiller is on so the heat is dissipated under it. Temperature range is from $+40^\circ C$ to $-40^\circ C$ ($-60^\circ C$). An NTC temperature probe is set under the SiPM to monitor the temperature. The readout of the NTC is done by an Arduino module. An alternative way to measure the temperature is to set a Pt100 on the aluminium holder and to read out the temperature on the external temperature probe input of the chiller. The Peltier device must be used with precaution because it induces noise. This noise will influence the measurements, especially when measuring low amplitude signals.

An LED light source is set in the box. The LED is operated in a pulsed mode. The trigger signal is given by the USB module which is going through a function generator that allows us to modify the light intensity and the delay applied on the pulses. A Keithley 2400 power supply is used to apply a bias to the SiPM, and common bias is used for all the channels. A channel by channel bias is also possible. A clear procedure was followed when handling the SiPMs to avoid damaging the detectors. A 50 Ohm resistor was placed on the bias connector, and an antistatic wristband was worn. A picture of the box and the USB board can be seen in Fig.(8).

Two measurements are needed to obtain the $V_{bd}$: the pedestal and the light spectrum. The pedestal is obtained by taking a measurement without applying any bias to the detector. The light spectrum is obtained by biasing the detector and sending light pulses. The pedestal will be subtracted from the signal. One hundred thousand events are enough for the pedestal or the light spectrum. The temperature was kept stable within 1K during the measure. The temperature during measurements is $23^\circ C$ but the $V_{bd}$ is compensate for $25^\circ C$.

To compute $V_{bd}$, the gain is measured for different $\Delta V$. The gain is given by the distance between two photon peaks of the low light spectrum. To reduce errors, this distance is measured over multiple peaks and then divided by the number of peaks minus one. This can be seen in Fig.(9). Then the gain is plotted as a function of $\Delta V$. By a linear fit, as in Fig.(10), and extrapolation for gain zero, one can find the $V_{bd}$ of the detector. This procedure has been automatized.
Figure 8: Setup inside the light tight box (taken from [9])

Figure 9: Light spectrum for $10^5$ events for KETEK wafer seven.

### 3.2 Cross-talk measurement

The VATA64 readout system is also used for the measurement of the cross-talk. This time the pedestal and the dark spectrum are needed. The dark spectrum is obtained when the detector is biased but no light is injected. The pedestal is subtracted from the signal. One
million events are needed for the dark spectrum. The cross-talk is obtained by taking the ratio between the integral of the signal between 0.5 photon and 1.5 photon:

$$X\text{-talk} = \frac{N_{\text{event}}(1.5 - \infty)}{N_{\text{event}}(0.5 - \infty)}$$

A typical dark spectrum can be seen in Fig.(11). Note that the trigger of the readout is not synchronised to the noise. As a consequence the photon peaks do not have a gaussian shape but reveal the random sampling of the pulse shape after the amplifier and shaper.

The shaping of the VATA64 can be seen in Fig.(12).

The cross-talk measured with the VATA64 includes after-pulsing. After-pulse will make the shaping of the VATA64 reach the 1.5 PE peak and will be considered as cross-
talk. A schematic can be found in Fig.(13). Cross-talk can also be measured with a Threshold scan (detailed in section 3.3). After-pulses are not included with the threshold scan because the peaks induced by after-pulses are below the thresholds and so are not taken into account. Therefore, this measurement gives a good estimate for the fast component of the after-pulsing.

![VATA64 readout is taking after-pulse in the measurement of the cross-talk. After-pulsing will make the shaping reach the 1.5 PE threshold and will be counted as cross-talk.](image)

**Figure 13:** VATA64 readout is taking after-pulse in the measurement of the cross-talk. After-pulsing will make the shaping reach the 1.5 PE threshold and will be counted as cross-talk.

### 3.3 Gain measurement

As the signal for KETEK detectors are very fast, part of the signal is filtered and therefore not accounted correctly in the VATA64 amplifier. A complementary setup was built to measure the gain. The idea is to measure the gain by counting the number of pulses within a certain time. This method is called TheThreshold Scan. For low thresholds, 1, 2 and more photon peaks will be detected. When the threshold is increased, only 2 and more photon peaks will be seen. A step function will be obtained as shown in Fig.(14). The cross-talk found with the VATA64 system can be cross-checked by taking the fraction between the 1.5 photon peak plateau and the 0.5 photon peak plateau. Note that the Threshold scan is very sensitive to the point taken for the 1.5 photon peak and so the value of the cross-talk may vary by 1 percent. Knowing the number of counts for the two flat steps, one can get the gain corrected for the cross-talk. The gain is given by:

$$G = \frac{I}{f_{\text{pix}} \cdot e}$$  \hspace{1cm} (7)

with $I$ the current, $e$ the elementary charge and $f_{\text{pix}}$ the firing frequency given by:

$$f_{\text{pix}} = \frac{\# \text{counts 1PE}}{\text{time interval}} + \frac{\# \text{counts 2PE}}{\text{time interval}}$$  \hspace{1cm} (8)

Note that the time interval is not given in absolute time with the threshold scan. A calibration was made and 1s = 3549 counts.

As the gain measurement can only be performed on one channel at a time, twelve channels are selected for the read out. These same twelve channels are used for the PDE
measurement. A small circuit was built to read out these channels. Note that the circuit needs to be shielded with copper tape to remove the high frequency noise. The noise induced by high frequencies can dominate the signal. For the same reason, detectors are placed inside a dark RF shielded box.

To avoid light leakage from the black box, a black cloth is placed over the setup. The LED serves as a noise generator and can be set in a continuous mode with a voltage around 2.8 V. This tension can be changed on the power supply to get the desired current on the SiPM. To allow a precise measurement of the current within 1% using the Keithley 2400, the current was set at 1 µA. If the picoammeter is used the current can be set lower. We get an uncertainty on the gain of around 5 %. The number of pulses in a 100 µs interval can be seen in Fig.(15). An histogram of the number of count for previous events can be seen in Fig.(16).

Figure 14: Step function obtained after a threshold scan for an Hamamatsu CB02 detector at \( \Delta V = 2.3 \) V. The flat steps are tilted due to the noise of electronics readout or due to the after-pluse.
3.4 Temperature coefficient measurement

To properly compensate $V_{bd}$ for the temperature, the temperature coefficient needs to be measured. The Peltier and the chiller will be used in order to reach a certain temperature. The chiller works in parallel with the Peltier and the box is flashed with dry air when going below 0°C to avoid condensation or icing. The NTC soldered on the flex close to the SiPM, or a Pt100 next to the detector (read out on the chiller), is used to monitor the temperature. To compute the temperature coefficient, one needs to find the breakdown voltage at different temperatures and make a linear fit to it. The temperature coefficient is then given by the slope of the fit. We have observed with the VATA64 that finding the gain (in ADC) for different temperatures is not reliable for KETEK detectors because the resistance of the detector changes for different temperatures. We expect the signal to be modified due to this such that the VATA64 does not integrate the complete signal of these detectors. The gain will be no longer proportional from one temperature to the other and so does the breakdown voltage.

To compute the temperature coefficient we measured the current as a function of the voltage applied (IV curves) using an irradiated detector at different temperatures. The IV curve is rescaled to get the current as a function of $\Delta V$ using $V_{bd}$ of the detector. The temperature coefficient is found in calculating the shift of the maximum of the derivative $\frac{dI}{dV}$ for different temperatures. This shift can be seen for three temperatures and two channels in Fig.(17)
3.5 Photo detection efficiency measurement

The photo detection efficiency measurement is done in a light tight box with a Xenon lamp used with a monochromator. The light output of the monochromator is coupled to an optical fibre going to a photo diode (PD) for calibration or to the SiPM. The wavelength set by the monochromator is controlled by a computer. As a reference, a 128 ch. Hamamatsu device was used and its PDE peak is set at 30 % [10].

![Diagram of the PDE setup](image)

**Figure 18:** Scheme of the PDE setup.

A schematic of the setup can be seen in Fig.(18). To avoid diffusion of the photons in the plexiglas protection which can induce undesired light on the detector, the protection was painted black and a large hole left open. The PDE relative to a calibrated photodiode...
will be determined. The relative PDE can be calculated using equation (9)

\[
PDE_{rel} = QE_{PD} \cdot \frac{I_{SiPM}}{I_{PD}}[11]
\]

The index PD stands for photodiode and \( I_{SiPM}, I_{PD} \) respectively are the current of the SiPM and the photodiode. The current of the SiPM is corrected for cross-talk and after-pulse. \( QE_{PD} \) is the quantum efficiency of the photo diode. Typical PDE curves can be seen in Fig.(19)

![Relative PDE w7c3FW](image)

**Figure 19:** Typical PDE curves for three channels and three \( \Delta \Delta V \).

Another parameter we are looking for is the PDE weighted by the light emission spectrum of the fibre. This parameter is called the photon yield and is given by:

\[
Photon\ Yield = \sum_{\lambda=420nm-550nm} PDE(\lambda) ES(\lambda) \Delta \lambda
\]

With \( PDE(\lambda) \) the PDE at a wavelength \( \lambda \), \( ES(\lambda) \) the emission spectrum of the fibre and \( \Delta \lambda \) the step in wavelength (here 5 nm). One can see the fibre emission spectrum in Fig.(20), and the emission spectrum is situated between 420 and 550 nm.
3.6 Irradiation

Irradiation of the detectors was performed in the Lotus reactor at EPFL. Three Pu-Be sources were used to get a square of 1 cm$^2$ homogenous neutron irradiation. Up to four multichannel arrays or 10s of 1 mm$^2$ single channel detectors can be irradiated simultaneously. A picture of the irradiation setup can be seen in picture (21).

The purpose of the irradiation is to measure the detector performance in the expected LHCb environment. For example, a 10 day irradiation ($\sim 2 \cdot 10^{11} n_{eq}/mm^2$) corresponds to one third of the dose expected during lifetime of the LHCb upgrade.

The irradiation increases the dark count rate (DCR). The DCR can be calculated from the measured current in an IV scan:

$$DCR = \frac{I}{G \cdot e}$$

(11)

with $I$ the current, $G$ the gain and $e$ the elementary charge. The DCR after irradiation can be reduced by annealing. Tests were made by warming the detectors to 40 degrees for A. Kuonen
seven days. This annealing process could be performed during LHC shutdowns in order to increase the lifetime of the detectors.

A possible way to express the efficiency of the cooling is the temperature difference required to make the dark current drop by a factor of two. We call this temperature difference $K_{1/2}$. This can be found by plotting the current on a log base two scale as a function of the temperature. Fitting this curve with an exponential one gets an equation like:

$$y = \alpha \cdot e^{\beta x}$$

(12)

The coefficient is then given by:

$$K_{1/2} = \frac{\ln(2)}{\beta}$$

(13)

A typical $K_{1/2}$ can be seen in Fig.(22)

![Figure 22: Typical $K_{1/2}$ plot (w3c3 c55 & c59).](image)

A. Kuonen
4 Results and discussion

The results obtained for the KETEK detectors are presented in this section. The summary of the results is given in Tab.(12).

4.1 Breakdown voltage

One of the properties we are interested in is the homogeneity of the breakdown voltage over the 64/128 channels. This will determine whether or not to bias each channel separately or if a common bias for all the channels is possible. We expect that the bias voltage should be the same for detectors from the same wafer. Typical results can be seen in Fig.(23) or Fig.(24).

![Figure 23: \( V_{bd} \) for w7c2 on all 64 channels with a maximum variation of 0.09 V.](image)

![Figure 24: \( V_{bd} \) for w3c3 on all 64 channels with a maximum variation of 0.13 V.](image)

The gain uniformity for these devices is sufficiently good to operate all channels of the detector at the same bias voltage. Gain or PDE differences due to the different \( V_{bd} \) are estimated to be sufficiently small for the SciFi Tracker application. The variations on the breakdown voltage are less than 0.2 V. Some outliers can be observed. These can come from a malfunctioning channel or a mis-estimation of the gain during the automatic gain determination procedure. Chips from same wafer show the same \( V_{bd} \) and this is true for all the wafers tested. The breakdown voltage found for all wafers can be seen in table (3)

<table>
<thead>
<tr>
<th>Wafers</th>
<th>Breakdown Voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1</td>
<td>~23.5</td>
</tr>
<tr>
<td>w3</td>
<td>~25.0</td>
</tr>
<tr>
<td>w7</td>
<td>~32.4</td>
</tr>
<tr>
<td>w8</td>
<td>~36.4</td>
</tr>
<tr>
<td>w9</td>
<td>~40.5</td>
</tr>
<tr>
<td>Hamamatsu CB02</td>
<td>~54.7</td>
</tr>
<tr>
<td>Hamamatsu std</td>
<td>~71.7</td>
</tr>
</tbody>
</table>

Table 3: Values of the breakdown voltage for various wafers.
4.2 Cross-talk and after-pulse

This section will focus on the measurement of the cross-talk with after-pulses included. The new trench technology is expected to have less cross-talk than the standard technology. On the standard technology we expect chip two to have less cross-talk than chip three. This is because the pixel size of chip three is bigger, the gain is therefore higher and the cross-talk is proportional to the gain. The opposite behaviour is expected on the new trench technology. Chip two has only $y$ trenches so it should have more cross-talk than chip three which has double trenches (i.e., on $x$ and $y$ axis). Typical results can be seen in Fig.(25) and Fig.(26).

![Figure 25: Cross-talk for w1c2 on all 64 channels. A value of 7% is reached at $\Delta V = 3.5$ V.](image)

![Figure 26: Cross-talk for w3c2 on all 64 channels. A value of 5% is reached at $\Delta V = 3.5$ V.](image)

A comparison between single and double trenches can be seen in Fig.(27). This shows the expected behaviour, where double trenches allows to the cross-talk to be reduced significantly. The cross-talk was also measured with the Threshold scan. This provided a good cross-check and the results can be seen in Table (4). One can see that the cross-talk found from the Threshold scan is systematically lower than the cross-talk found with the VATA64. This confirms that the VATA64 includes the after-pulse.

<table>
<thead>
<tr>
<th></th>
<th>w1c2</th>
<th>w1c3</th>
<th>w2c2</th>
<th>w2c3</th>
<th>w3c2</th>
<th>w3c3</th>
<th>w4c2</th>
<th>w4c3</th>
<th>w7c2</th>
<th>w7c3</th>
</tr>
</thead>
<tbody>
<tr>
<td>VATA64 Measurements</td>
<td>7 %</td>
<td>9 %</td>
<td>7 %</td>
<td>7 %</td>
<td>5 %</td>
<td>6 %</td>
<td>5 %</td>
<td>3 %</td>
<td>5.5 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Threshold Measurements</td>
<td>6 %</td>
<td>8 %</td>
<td>5.7 %</td>
<td>7 %</td>
<td>3.5 %</td>
<td>1.4 %</td>
<td>5 %</td>
<td>1.3 %</td>
<td>5 %</td>
<td>1.6 %</td>
</tr>
</tbody>
</table>

Table 4: Cross-talks for various wafers measured using two different methods at $\Delta V = 3.5$ V.

4.3 Gain

Gain measurements were done first using the VATA64 readout to measure the distance between two photon peaks in the light spectrum. This method had to be abandoned because the VATA64 did not integrate the complete fast pulse signal of the KETEK detectors and so miscalculated the gain. The Threshold scan was used instead. The gain
Figure 27: Comparison between single and double trench for different chips.

is expected to be bigger for chip 3 than for chip 2 as the pixel size is bigger for chip 3. Note that the detector is a capacitor so the detectors with an epitaxial layer should have a lower gain. Typical gain values can be seen in Table (5).

<table>
<thead>
<tr>
<th>Wafer</th>
<th>Wafer 3</th>
<th>Wafer 7</th>
<th>Wafer 8</th>
<th>Wafer 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip 2</td>
<td>8.3E+06</td>
<td>8.2E+06</td>
<td>6.5E+06</td>
<td>5.8E+06</td>
</tr>
<tr>
<td>Chip 3</td>
<td>12.1E+06</td>
<td>12.2E+06</td>
<td>9.4E+06</td>
<td>8.2E+06</td>
</tr>
</tbody>
</table>

Table 5: Gains for various wafers and chips measured at $\Delta V = 3.5$ V.

One can see that, as expected chip two has less gain than chip three. Wafer one and three have no epitaxial layer and so the gains are the same. Nevertheless w7, w8 and w9 have different sizes of epitaxial layer (Tab.(1)), which could explain the different measured gains. The gain of w9 can not be trusted because the current was not stable due to humidity. We observed that the gain decreases as the size of the epitaxial layer increases, which is the expected behavior.

4.4 Photo detection efficiency

A typical PDE spectrum can be seen in Fig.(28). Three channels with three $\Delta V$ were plotted for every available wafer. The PDE increases with the $\Delta V$ as expected. A good homogeneity between channels can also be seen. The maximum PDE and the corresponding wavelength were determined. The results are given in Tab.(6).

Moreover knowing the emission spectrum of the fibre, we are interested to know the photon yield. The PDE outside the emission spectrum of the fibre is not relevant. Looking at the PDE of the KETEK detectors, one can see that the position of the peak is around 420 nm where the emission spectrum of the fibre is zero. It is interesting to compare the standard Hamamatsu, new Hamamatsu technology (CB02) and KETEK detectors. New
Hamamatsu detectors have a lower PDE peak value but are more constant between 420 nm and 550 nm where the KETEK has a high PDE peak which decreases quickly. The photon yield can be seen in Tab.(7).

The new Hamamatsu CB02 detector has a better photon yield than all the KETEK detectors except for w1c3 that is comparable at $\Delta V = 3.5$ V.

Looking at Fig.(29), one can see that the gain of PDE after $\Delta V = 4.5$ V is smaller. The gain in PDE for $\Delta V = 2.5$ V, 3.5 V and 4.5 V is around four percent but only one to two percent for $\Delta V = 5.5$ V and 6.5 V. Note that the cross-talk and after-pulse is corrected in reducing the current by the cross-talk plus after-pulse percentage. So as it increases at higher voltage it should also lead to more signal detected at a higher over voltage as shown in the scan.

One can see in Fig.(30) that the PDE maximum saturates and does not increase after 4.5 V over-voltage and that the PDE when the cross-talk and after-pulse is not corrected is higher than the corrected one. The photon yield can also be seen in Fig.(31). However, the

<table>
<thead>
<tr>
<th>PDE Peak [%]</th>
<th>Wavelength peak [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1c2</td>
<td>42</td>
</tr>
<tr>
<td>w1c3</td>
<td>44</td>
</tr>
<tr>
<td>w3c2</td>
<td>39</td>
</tr>
<tr>
<td>w3c3</td>
<td>41</td>
</tr>
<tr>
<td>w7c2</td>
<td>39</td>
</tr>
<tr>
<td>w7c3</td>
<td>40</td>
</tr>
<tr>
<td>w8c2</td>
<td>33</td>
</tr>
<tr>
<td>w8c3</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 6: PDE peak at $\Delta V = 3.5$ V and corresponding wavelength for various wafers and chips.
Table 7: Photon yield. Red cases show the detector with the most photon yield for the three benchmarks. Emission spectrum simulated for a fibre irradiated to 35kGy in centre (LHCb like graded to the outside).

peak is green shifted as the over-voltage increases (Fig.(29)). This results in an increase of the photon yield.

![Relative PDE w4c3 ch68 for different OV](image)

Figure 29: PDE scan of w4c3 for different ΔV.
Figure 30: PDE peak of w4c3 for different ∆V with cross-talk and after-pulse corrected (black) or not (red).

Figure 31: Photon yield for w4c3 for different ∆V with cross-talk and after-pulse corrected.

Table 8: Photon yield obtained for w4c3 at various ∆V.

<table>
<thead>
<tr>
<th>Detectors</th>
<th>35kGy 0cm</th>
<th>35kGy 100cm</th>
<th>35kGy 250cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>w4c3 (1.5ov)</td>
<td>0.97</td>
<td>1.03</td>
<td>1.10</td>
</tr>
<tr>
<td>w4c3 (2.5ov)</td>
<td>1.23</td>
<td>1.30</td>
<td>1.39</td>
</tr>
<tr>
<td>w4c3 (3.5ov)</td>
<td>1.39</td>
<td>1.47</td>
<td>1.56</td>
</tr>
<tr>
<td>w4c3 (4.5ov)</td>
<td>1.51</td>
<td>1.59</td>
<td>1.68</td>
</tr>
<tr>
<td>w4c3 (5.0ov)</td>
<td>1.56</td>
<td>1.64</td>
<td>1.73</td>
</tr>
<tr>
<td>w4c3 (6.0ov)</td>
<td>1.59</td>
<td>1.67</td>
<td>1.76</td>
</tr>
<tr>
<td>w4c3 (7.0ov)</td>
<td>1.63</td>
<td>1.71</td>
<td>1.79</td>
</tr>
<tr>
<td>w4c3 (8.0ov)</td>
<td>1.65</td>
<td>1.73</td>
<td>1.81</td>
</tr>
<tr>
<td>New Hamamatsu CB02 (3.5ov)</td>
<td>1.61</td>
<td>1.66</td>
<td>1.70</td>
</tr>
<tr>
<td>Hamamatsu Standard (1.3ov)</td>
<td>1.26</td>
<td>1.30</td>
<td>1.33</td>
</tr>
</tbody>
</table>

The integral of the PDE weighted by the light emission spectrum was redone and can be seen in Tab.(8). The photon yield for the KETEK starts to become higher than the CB02 for 5.5 V over-voltage. At 8.5 V over-voltage for 250cm, the photon yield is 5 % higher than the CB02 at the same benchmark.
4.5 Irradiated detectors

Seven wafers were irradiated. The dose they received was:

- Wafers 8 and 9: $1.75 \times 10^{11} \text{ n}_{eq}/\text{cm}^2$
- Wafers 1, 3 and 7: $2.14 \times 10^{11} \text{ n}_{eq}/\text{cm}^2$

Wafers 7, 8 and 9 are expected to show less effect from radiation due to their epitaxial layer that should prevent damage from radiation. IV curves were performed.

In Fig.(32) one can see typical IV curves for w3c3. At the same time, the derivation: \( \frac{dI}{dV} \) was performed to find the temperature coefficient. The maximum of the derivative is always at zero for each temperature (Fig.(33)). To achieve this, the temperature coefficient was set at -18mV/K. The same procedure was applied for the six other irradiated wafers. Table (9) shows the temperature coefficient for each wafer. The temperature coefficient seems to increase proportionally with the breakdown voltage. This can be observed in Fig.(34).

<table>
<thead>
<tr>
<th>Wafers</th>
<th>Temperature coefficient [mV/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1c2</td>
<td>$\sim -15.0$</td>
</tr>
<tr>
<td>w3c3</td>
<td>$\sim -18.0$</td>
</tr>
<tr>
<td>w7c3</td>
<td>$\sim -22.0$</td>
</tr>
<tr>
<td>w8c2/3</td>
<td>$\sim -23.0$</td>
</tr>
<tr>
<td>w9c2/3</td>
<td>$\sim -26.0$</td>
</tr>
<tr>
<td>Hamamatsu CB02</td>
<td>$\sim -43.0$</td>
</tr>
<tr>
<td>Hamamatsu std</td>
<td>$\sim -56.0$</td>
</tr>
</tbody>
</table>

Table 9: Values of the temperature coefficient for various detectors types
Figure 33: $dI/dV /I$ curves for w3c3 for two channels (55, 59) and three temperatures: -20°C, -30°C, -40°C. The curves are corrected with the temperature coefficient.

Figure 34: Linear fit of the temperature coefficient as a function of the breakdown voltage.

The dark count rate was calculated according to equation (11). Typical dark count rates for different over-voltages can be seen in Fig.(35). The DCR is shown for two channels and for the three measured temperatures: -20°C, -30°C, -40°C.

The DCR for w3c3 is around 25.7 MHz at $\Delta V = 3.5$ V and -40 °C. The dark count rate for all the irradiated detectors at -40 °C can be seen in Fig.(36). Wafer 9 chip 2 shows less DCR compared to all the others detectors. Wafers 8 and 9 have significantly less cross-talk than the others, meaning that the epitaxial layer seems to have an influence on damage due to irradiation. The DCR is around two times less for wafers 8 and 9 than
for wafer 1, 3 and 7. The DCR is smaller in chips two than in chips three which can be explained by the smaller pixel size of chip two.

All seven detectors were annealed for one week at 40°C. We expect to see a lower DCR after annealing. Table (10) shows the DCR reduction obtained for the different detectors after annealing at -40 degrees:

<table>
<thead>
<tr>
<th>Detector</th>
<th>DCR before ann. [MHz]</th>
<th>DCR after ann. [MHz]</th>
<th>DCR Reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1c2 (2.5 ov)</td>
<td>25.5</td>
<td>13.8</td>
<td>46</td>
</tr>
<tr>
<td>w3c3 (3.5 ov)</td>
<td>25.7</td>
<td>18.2</td>
<td>29</td>
</tr>
<tr>
<td>w7c3 (3.5 ov)</td>
<td>20.7</td>
<td>12.3</td>
<td>40</td>
</tr>
<tr>
<td>w8c2 (3.5 ov)</td>
<td>10.3</td>
<td>6.4</td>
<td>38</td>
</tr>
<tr>
<td>w8c3 (3.5 ov)</td>
<td>13.1</td>
<td>8.6</td>
<td>35</td>
</tr>
<tr>
<td>w9c2 (3.5 ov)</td>
<td>6.3</td>
<td>3.8</td>
<td>39</td>
</tr>
<tr>
<td>w9c3 (3.5 ov)</td>
<td>8.2</td>
<td>6.9</td>
<td>17</td>
</tr>
<tr>
<td>H. std (1.3 ov)</td>
<td>X</td>
<td>2.4 [13]</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 10: Dark count rate before and after annealing the irradiated detectors at -40°C.

On average the reduction in DCR after one week of annealing is around 35%. The DCR for the seven detectors, after annealing, at -40 degrees can be seen in Fig.(37). One can see that w8 and w9 still have less DCR than w1, 2, 3. Note that w9c3 behaves strangely above $\Delta V = 3$ V. This could come from the humidity because w8, 9 are very sensitive to it, and this may cause short cuts. The bump in the DCR curve for w9c3 explains also the relative small decrease of DCR. The DCR reduction for w9c3 at $\Delta V = 2.5$ V is around 35 % which corresponds better with the other detectors. The noise of the KETEK is still higher than the noise of the Hamamatsu. Note that annealing is also taking place during irradiation, a larger effect would be observed if irradiated cold.
Figure 36: DCR after irradiation for w1c2, w3c3, w7c3, w8c2/3 and w9c2/3 at -40°C.

Figure 37: DCR after annealing for w1c2, w3c3, w7c3, w8c2/3 and w9c2/3 at -40°C.
The coefficient $K_{1/2}$ was found for each KETEK wafer and can be seen in the Tab.(11). The KETEK detectors need a much larger temperature difference to make the dark current drop by a factor two.

<table>
<thead>
<tr>
<th></th>
<th>$K_{1/2}$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1c2</td>
<td>18.7</td>
</tr>
<tr>
<td>w3c3</td>
<td>24.1</td>
</tr>
<tr>
<td>w7c3</td>
<td>18.6</td>
</tr>
<tr>
<td>w8c2</td>
<td>14.3</td>
</tr>
<tr>
<td>w8c3</td>
<td>14.3</td>
</tr>
<tr>
<td>w9c2</td>
<td>12.9</td>
</tr>
<tr>
<td>w9c3</td>
<td>14.9</td>
</tr>
<tr>
<td>H. std</td>
<td>10</td>
</tr>
<tr>
<td>H. CB02</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Table 11: Temperature needed to make the dark current drop by a factor two ($K_{1/2}$).
4.6 Damaged detectors

One issue encountered during the manipulation of the detector was the large amount of broken channels. Some wafers showed more than 50% dead channels. After talking with KETEK, it appears that the detectors are not passivated and so are very sensitive to humidity and handling. For example, humidity could be a big issue on wafers 8 and 9. Some pictures of the KETEK detectors were taken under a microscope to look at the damage.

![Typical corrosion or burn marks on a detector on wafer 7 chip 2.](image1)

![W2C2 corrosion and black spots across the pixel boundary.](image2)

We see a presence of black spot due to corrosion or burning like in Fig.(38). These black spots seem to be concentrated into the boundary of the pixels and so seem to be an effect happening within a pixel and not a global issue. This can be seen in Fig.(39). The references do not show such black spot like in Fig.(40). This problem should be solved in the future by passivating the silicon.

![W1 test part, not exposed to humidity in the lab, proper.](image3)
4.7 Summary

The results of all measurements are given in Tab. (12).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>wfc1_part1</td>
<td>~23.4</td>
<td>~7%</td>
<td>~6%</td>
<td>49/64</td>
<td>49/64</td>
<td>54/64</td>
<td>1.2E-07</td>
<td>8.2E+06</td>
<td>~41%</td>
</tr>
<tr>
<td>wfc1_part2</td>
<td>~23.6</td>
<td>~9%</td>
<td>~8%</td>
<td>62/64</td>
<td>62/64</td>
<td>62/64</td>
<td>1.1E-07</td>
<td>8.2E+06</td>
<td>~43%</td>
</tr>
<tr>
<td>wfc2_part1</td>
<td>~25.0</td>
<td>~6%</td>
<td>~5%</td>
<td>57/64</td>
<td>57/64</td>
<td>57/64</td>
<td>1.3E-07</td>
<td>8.1E+06</td>
<td>~44%</td>
</tr>
<tr>
<td>wfc2_part2</td>
<td>~25.0</td>
<td>~5%</td>
<td>~4%</td>
<td>60/64</td>
<td>60/64</td>
<td>60/64</td>
<td>8.1E+06</td>
<td>8.1E+06</td>
<td>~45%</td>
</tr>
<tr>
<td>wfc3_part1</td>
<td>~25.0</td>
<td>~5%</td>
<td>~5%</td>
<td>49/64</td>
<td>49/64</td>
<td>49/64</td>
<td>6.5E+06</td>
<td>8.1E+06</td>
<td>~46%</td>
</tr>
<tr>
<td>wfc3_part2</td>
<td>~25.0</td>
<td>~5%</td>
<td>~5%</td>
<td>49/64</td>
<td>49/64</td>
<td>49/64</td>
<td>6.5E+06</td>
<td>8.1E+06</td>
<td>~47%</td>
</tr>
<tr>
<td>wfc4_part1</td>
<td>~32.4</td>
<td>~5%</td>
<td>~5%</td>
<td>30/64</td>
<td>30/64</td>
<td>30/64</td>
<td>5.8E+06</td>
<td>5.8E+06</td>
<td>~48%</td>
</tr>
<tr>
<td>wfc4_part2</td>
<td>~36.7</td>
<td>~7%</td>
<td>~6%</td>
<td>50/64</td>
<td>50/64</td>
<td>50/64</td>
<td>5.8E+06</td>
<td>5.8E+06</td>
<td>~49%</td>
</tr>
</tbody>
</table>

Table 12: Complete results obtained for the KETEK detectors.
5 Conclusion

This work showed that the KETEK detectors have promising features for the proposed SciFi Tracker but they still need some improvements. The cross-talk is particularly low, especially for the wafers with the new additional trenches. The temperature dependence is also low and this will help with the cooling of the detectors, and make it easier to operate. However, the dark count rate is higher than for the Hamamatsu detectors after irradiation. The epitaxial layer seems to consequently decrease the damage done by neutron radiation. The annealing also helps the detector to reduce the noise as expected. At this point, KETEK detectors seems less appropriate for the LHC radiation environment then the Hamamatsu. For the PDE, the new Hamamatsu CB02 and the KETEK have nearly the same photon yield. KETEK have a higher PDE peak but is less well adapted to the emission spectrum of the fibre. The photon yield could significantly increase if the PDE peak could be green shifted. This was tried by KETEK but the PDE peak was too low and the detectors were too noisy. Moreover, the detectors seem to be very sensitive to humidity and handling. The reliable packaging needs to be demonstrated, passivation is probably inevitable.

6 Acknowledgments

First of all, I want to thank my supervisor, Guido Haefeli for all the advice and experience he shared with me. He was always available for questions and I have learnt a lot thanks to him. I want also to thank Mark Tobin for the reading and the corrections of my report. Thanks also to Sebastiana Gianì for all the help she provided me on the analysis programs and for coming with me on a weekend to redo measurements. To Raymond Frei and Guy Masson thanks for all their advices in electronics and for the numerous Pt100 they provided us. Also thanks to all the mechanician team for their rapidity in doing the pieces I needed. To Leonardo Lessa for the temperature read-out and the help with the computers. To finish I want to thank Olivier Girard that endured me in our office and who was always ready to help me or laugh at good jokes.
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