Temperature and Bias Voltage Dependence of the

MPPC Detectors

N. Dinu, C. Bazin. V. Chaumat, C. Cheikali, A. Para, *Member, IEEE*, V. Puill, C. Sylvia, J.F. Vagnucci

***Abstract–*This work reports on the characterization of the**

**Multi-Pixel Photon Counter (MPPC) detectors as a function of**

**the temperature and bias voltage. Devices of 1x1 mm2 and 3x3**

**mm2 total area and 50x50 μm2 μcell size produced by**

**Hamamatsu Photonics have been studied. The temperature has**

**been varied from -110°C to -50°C using a cryostat cooled by**

**liquid nitrogen and from 0 to 38°C using a climatic chamber.**

**Important electrical parameters of the MPPC detectors as gain,**

**breakdown voltage, quenching resistance, capacitance and dark**

**count rate have been measured.**

I. INTRODUCTION

OWADAYS, the MPPC detector has become an attractive

photon detector for physics applications as well as for

medical imaging (e.g. ND280 & INGRID for the T2K [1],

CALICE for the ILC [2], scintillation read-out in liquid argon

particle physics detectors [3], Positron Emission Tomography

[4]).

The temperature and the bias voltage represent two

parameters affecting important electrical characteristics of the

MPPC detectors and consequently their response to the

incident light. In particular, static parameters such as

breakdown voltage, capacitance and quenching resistance and

dynamic parameters as gain and dark count rate exhibit strong

variations as a function of temperature. The dark count rate

scales with the active area of the device and it has strong

dependence on the applied bias voltage.

This paper presents a description of the main electrical

characteristics of the MPPC detectors and their dependence of

temperature. The dedicated set-ups developed for the

characterization of these detectors as a function of temperature

will be described. The characteristics of the MPPC detectors

produced by Hamamatsu Photonics [5] with a μcell size of

50x50 μm2 and covering a total area of 1x1 mm2 and 3x3 mm2

have been measured and a comparative analysis of their

performances is presented.

II. EXPERIMENTAL

*A. The MPPC characteristics and work motivation*

The MPPC detector is a kind of so-called SiPM (Silicon

Photomultiplier) devices [6]. It consists of hundreds of microcells

(μcell) connected in parallel by a common silicon

N. Dinu, C. Bazin, V. Chaumat, C. Cheikali, C. Sylvia, J.F. Vagnucci are

with the Laboratory of Linear Accelerator & University Paris 11,

CNRS/IN2P3, 91898 Orsay Cedex, France (telephone: +33 1 64468966, email:

dinu@lal.in2p3.fr).

A. Para, is with Fermi National Accelerator Laboratory, Batavia, IL

60510-5011 USA. (telephone: 630-840-4935, e-mail: para@fnal. gov).

substrate (on the rear side) and by a metal layer (on the front

side). Each μcell is represented by a p+/n junction working in

Geiger-mode connected in series with its integrated passive

quenching resistance.

The detectors are operated with each μcell biased to a bias

voltage Vbias above the breakdown voltage VBD. The Vbias

exceeds the VBD by an amount called overvoltage V = Vbias –

VBD, which has a critical influence on detector performance

(e.g. the ratio V/VBD is related to the excess electric field

above the breakdown level). It is expected that the VBD of a

p+/n silicon junction decreases with decreasing temperature T

(e.g. larger carrier mobility, larger ionization rates and lower

potential difference for ionization at low T and constant

electrical field [7]). Therefore, to keep constant operational

conditions of the MPPC detectors (e.g. constant electrical

field), the variation of the VBD as a function of T is required to

be evaluated.

A primary carrier generated in the depleted region of a

MPPC μcell by an incident photon or a thermal generated

carrier produces an avalanche resulting in high current signal

flowing through the junction. The continuous flow of this is

limited by the quenching resistance Rq, which quenches the

avalanche and reduces the Vbias to VBD or below. The Vbias is

subsequently restored with a recovery time constant r

depending on the values of the Rq and μcell capacitance Cμcell

(r ~ 5•RqCμcell for a 99% recharge).

The Rq of the MPPC devices is fabricated by a deposition of

poly-silicon. The resistance of a poly-Si varies with T, the rate

of variation depending on the dopant type and concentration

[8]. Therefore, the time required to recover the μcell operation

voltage and to be able to detect another photon varies with T

and consequently this dependence is necessary to be

determined.

The effective capacitance of a μcell Cμcell is given by the

sum of the junction capacitance Cd and a parasitic capacitance

Cq, in parallel with Rq. Given the importance of the μcell

capacitance for the operational characteristics of the MPPC, it

is very important to investigate possible variations of this

parameter with the operating temperature of the device.

Other electrical parameters dominating the performances of

a MPPC device in many applications are as follows: (1) the

gain (G), defined as the total charge of the Geiger avalanche

divided by the electron charge; and (2) the dark count rate

(DCR), defined as the number of avalanches per second

registered in the absence of light.

The Geiger avalanche charge is proportional to the

overvoltage (Q = Cμcell V). At constant V, some variations

of the G with T may be expected (for example as a result of

variation of Cμcell) and they should be studied experimentally.

The DCR includes primary and secondary pulses [9].

Primary dark pulses are due to carriers thermally generated in

the μcell p+/n junction, hence the count rate increases with the

T as does the dark current in ordinary photodiodes. This rate

also increases with V because of two effects, namely, fieldassisted

enhancement of emission rate from generation centers

and an increase of the avalanche triggering probability.

Secondary dark pulses are due to afterpulsing and cross-talk

effects and they may account for a large fraction of the total

DCR.

During the avalanche some carriers are trapped by deep

levels in the junction depletion layer and subsequently

released with statistically fluctuating delay, whose mean value

depends on the life time of the deep levels actually involved.

Released carriers can trigger a subsequent avalanche,

generating afterpulses correlated with a previous avalanche

pulse. The traps lifetime depends on T, therefore the

afterpulsing rate is expected to vary with T. The number of

carriers captured during a Geiger avalanche increases with the

total number of carriers crossing the junction, that is with the

total charge of the avalanche pulse which is proportional to the

V.

In avalanching p+/n junctions the emission of hot-carrierinduced

photons is a phenomenon already evidenced [10].

Such photons can trigger avalanches in adjacent μcells

generating simultaneously signals with the primary ones - a

phenomenon called optical cross-talk.

Given the importance of the temperature and overvoltage

for the different DCR components, an evaluation of this

parameter as a function of T and V represent an important

study to be performed.

*B. Measurements set-up*

Two experimental set-ups have been developed for the

measurements presented in this paper: one using a

programmable climatic chamber with T range 0°C<T<38°C

and a second one using a liquid nitrogen cryostat with T range

-110°C<T< -50°C. The T of the cryostat was controlled by a

heater (R~20) and stabilized by a cryogenic control system

(Cryo.con model 22) for setting the heater current while the T

of the climatic chamber was controlled by a ventilation

system. In both set-ups, the T has been monitored by a Pt100

sensor mounted close to MPPC detector and read-out by a

Keithley 2000 multimeter. To obtain reproducible results, the

measurements have been carried out only when a good

thermal equilibrium has been attend (e.g. ± 0.1°C around

assigned T).

The MPPC tests in the cryogenic set-up have been carried

out under vacuum conditions at P ~ 1.5x10-3mbar while the

tests in the climatic chamber have been performed at

atmospheric pressure.

Equivalent data acquisition systems have been build to both

set-ups:

- the IV static characteristics (e.g. Rq) have been

obtained by a direct connection of the MPPC detector

to the Keithley 2611 source-meter;

- the AC characteristics (e.g. G, Cμcell, DCR) have been

measured biasing the MPPC detector by a Keithley

2611 source-meter and reading-out by MITEQ wideband

voltage amplifier (0.01 – 500 MHz) connected to

a Tektronix digital oscilloscope (500 MHz, 5 GS/s).

The amplifier presents 50 input impedance, which

acts as a current-to-voltage converter followed by an

amplifying stage having a gain of 45 dB. In particular

for the DCR measurements at low T, when long

counting time of 10 s was required to measure DCR of

the order of Hz, the amplifier output signal has been

connected to a counter.

To reduce the electromagnetic noise, the amplifier has been

connected as close as possible to the detector. For the cryostat

set-up, the amplifier has been connected outside of the

cryostat to avoid the amplifier gain variation as a function of

T. For the climatic chamber set-up, the amplifier gain

variations have been evaluated to be less than 5% in the T

range from 0° to 38°C and therefore the amplifier was

mounted inside of the climatic chamber.

For the automated data acquisition, the Keithley source

meter and multimeter, the counter as well as the Tektronix

oscilloscope have been run by LabView and C++ programs

through GPIB and USB connections. More details on the

measurement of each parameter and data analysis methods

will be given in the Section III.

III. CHARACTERISTICS OF THE MPPC DEVICES

Based on the statement that primary signals generated by a

thermally generated carrier or by an incident photon in a

MPPC μcell are identical, all results presented in the following

were measured in dark conditions.

The analyzed detectors present different total areas (1x1

mm2 and respectively 3x3 mm2), but the same μcell size (e.g.

50x50 μm2). Therefore, a good uniformity as well as a very

similar dependence of the measured parameters with respect to

T are expected over analyzed detectors. Moreover, the only

parameter which should present significant different values is

the DCR since it is directly related to the total active area of

the detector.

The G of the MPPC detectors has been determined from

time integration of the single photoelectron signal seen on the

oscilloscope during an integration window adapted on the

signal shape (e.g. to collect 99% of the charge). The results of

these measurements as a function of Vbias at different T are

presented in Figs. 1. a) and b).

Independent on the measured detector, at a given T, the G

increases linearly with Vbias as expected (e.g. G ~ Cμcell (Vbias

- VBD)). The VBD, determined from the intersection of the

linear fits with abscise axis, shows a linear increase with T

ranging from -110°C up to 38°C (Fig. 2.), with a temperature

coefficient of ~ 58.5±0.5 mV/°C for both analyzed detectors.

Independent on the measured detector, at a given Vbias, the

G decreases with T. Since this dependence is strongly related

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to the variations of the VBD with T, a much more uniform G

values are expected if the V is maintained constant for

different T.

Fig. 1. The G vs Vbias for the MPPC of 1x1 mm2 (a) and 3x3 mm2 (b) at

different temperatures.

Figs. 3. a) and b). present the G dependence of V. The G

increases linearly with V, with values ranging from 2.5x105

to 1.5x106 when V varies from 0.5V to 2.5V. Maximum gain

variations of 20% are observed at a given V.

Variations of the G with T at constant V can be interpreted

as the dependence of the μcell capacitance on T. The Cμcell is

calculated from the slope of the G vs V and their variations

as a function of T are represented in Figs. 4. a) and b) (blue

dots). The Cμcell shows a quadratic dependence of T, with

values increasing from 90 to 110 fF and from 70 to 90 fF

when T increases from -100°C to 38°C for the MPPC of 1x1

mm2 and respectively 3x3 mm2.

Fig. 2. The VBD vs T for the MPPC of 1x1 mm2 and 3x3

mm2

Fig. 3. The G vs V for the MPPC of 1x1 mm2 (a) and 3x3

mm2 (b) at different temperatures.

Fig. 4. The Rq vs Cμcell as a function of T for the MPPC of 1x1 mm2 (a)

and 3x3 mm2 (b).

Figs. 4. a) and b) present also the Rq (red dots) as a function

of T (e.g. calculated from the linear fit of IV forward

characteristic). The Rq exhibits a quadratic variation, with

decreasing values when T increases. The MPPC detector with

an area of 1x1 mm2 shows Rq values ranging from ~240 kto

~90 kwhen T varies from -100°C to 38°C and the detector

with an area of 3x3 mm2 shows Rq values from ~460 kto

~150 kfor the same T range. The higher Rq values of 3x3

mm2 detector with respect to the 1x1mm2 one are probably

related to changes in the fabrication of the detectors.

Variations of Rq and Cμcell with temperature leads to

significant variation of the μcells recovery time constant r and

the shape of the detector signal with the T. Figs. 5. a) and b)

show normalized single photoelectron signal shapes for

different temperatures. Consequently, the signal integration

gate, calculated as 5 • r for 99% recovery, decreases from 120

to 50 ns and from 300 to 160 ns for T increasing from -100°C

to 38°C for the MPPC of 1x1 mm2 and respectively 3x3mm2

area.

Fig. 5. The shape signal and the r for different T for the MPPC of 1x1

mm2 (a) and 3x3 mm2 (b).

The DCR versus V has been also measured for

-100°C<T<38°C (Figs. 6. a) and b)). At a given T, an

exponential increase of the DCR has been observed for V

increasing up to 2.5V. At a given V, the DCR increases with

T over many orders of magnitude.

The DCR is proportional to the free carrier density. The

dependence of carrier density on T is given by the relation: A •

T1.5exp(-Eact/kT), where A is a constant, T is the temperature

in K, k is the Boltzmann constant and Eact represents the

thermal activation energy. Fitting the DCR versus 1/T in the

temperature range -60°C to 38°C with a form A • T1.5exp(-

Eact/kT) yields an estimation of Eact of about 0.54 eV (Fig. 7).

A deviation of the experimental points from the fitted line

has been observed for T lower than -60°C, for both

investigated detectors and different overvoltages. This is

probably an indication of a different mechanism of generation

of free carriers in the conduction band with much weaker

dependence on the temperature. Similar results were recently

reported in [11].