CMS ECAL APD quality assurance facility

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Abstract

The S8148 Avalanche Photo Diode (APD), developed by Hamamatsu Photonics for CMS electromagnetic calorimeter fits well to the detector specifications. The dedicated quality assurance/control facility is installed at CERN by CMS MINNEUPSI (Minnesota University + Northeastern University + Paul Scherre Institute) collaboration, for APD input control during the mass production.

I. INTRODUCTION

A high discovery potential of the CMS experiment should be based on an excellent performance of all sub-detectors, in particular the electromagnetic calorimeter (ECAL) [1]. This detector will be made of two innovative materials never used in calorimetry before: heavy and fast $PbWO_4$ scintillating crystal read out by the large area Avalanche Photo Diode. The latest one was developed by Hamamatsu Photonics for CMS ECAL following a very demanding specification: the best possible parameters essential for the calorimeter performance, like high quantum efficiency, low dark current etc., and very good stability and reliability.

The R&D on APD optimisation is practically finished and the current device parameters (see below) fit well to the CMS ECAL specification. The reliability issue is becoming crucial now, in particular the way of APD testing during the mass production to ensure 10^{-4} fault rate required by specification. To address this problem, the CMS collaboration has created the APD Laboratory at CERN and has equipped it by several computer controlled test benches dedicated to the APD quality assurance and quality control during the mass production.

II. APD STATUS

The electromagnetic calorimeter performance is usually expressed in terms of the energy resolution, which is parameterised as: $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$, where the stochastic term *a* is due to the intrinsic shower fluctuation combined with the photo statistics, the constant term *b* is related to the detector stability, uniformity and precision of the calibration and the term *c* is the noise contribution due to electronics, pile-up etc. The CMS ECAL design goal is : *a*~3%, *b*~0.5% and c~200 MeV [1]. APD contributes to all three terms: to the stochastic term *a* by photo statistics, in particular by APD area and quantum efficiency and by the excess noise factor F [2], which reflects the avalanche nature of the photo multiplication by APD; to the constant term *b* by the gain variation with bias voltage and temperature, ageing and radiation damage effects; to the noise term *c* by the capacitance as a series noise and the dark current as a parallel noise. The goal of R&D was to maximise the ‘useful’ parameters like APD area, quantum efficiency and minimise the ‘bad’ parameters like excess noise factor, dark current, capacitance and the slopes of the bias voltage and temperature dependencies.

A. APD parameters

The final values of the essential APD parameters are summarised in Table. 1

Table 1: Hamamatsu S8148 APD parameters

Active area	$5x5mm^2$
Operating voltage(Vr)	~380V
Capacitance	70pF
Serial resistance	3Ω
Dark Current	<10nA
Quantum Efficiency	~72%@420nm
$1/M^{a)}$×dM/dV(M=50)	3.3%
1/M×dM/dT(M=50)	-2.3%
Excess Noise Factor (M=50)	2
Distance to breakdown (Vb-Vr)	(30-40)V
Effective thickness	~5µm
Gain range	Up tp 1000

[a)] M is a gain value, T-temperature

The typical APD gain curve is shown in Figure 1. It is clear that the gains up to several hundreds can be used. The gain dependence on the bias voltage and the temperature are shown in Figure 2. The example of the capacitance, quantum efficiency and excess noise factor curves are shown in figures 3, 4 and 5 respectively.

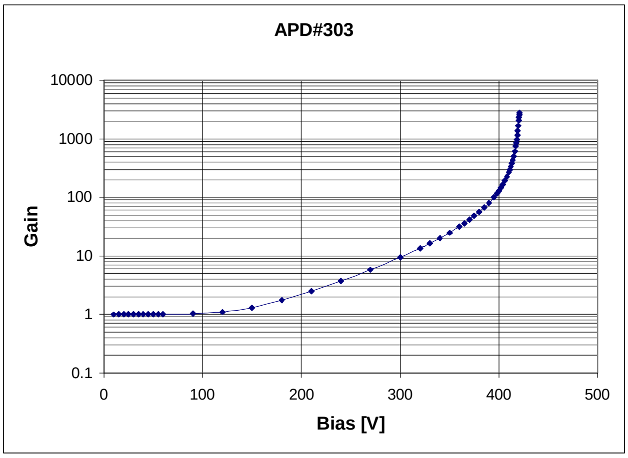

Figure 1: The typical APD gain vs. bias voltage curve.

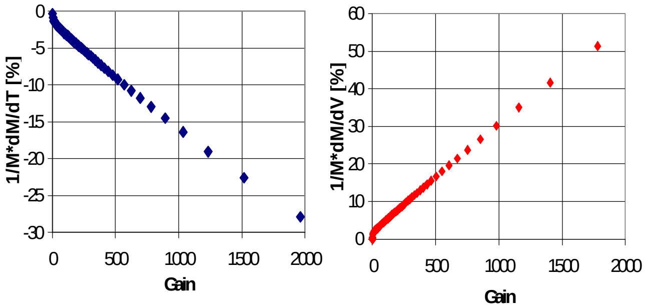

Figure 2: The gain dependence on the bias voltage and temperature.

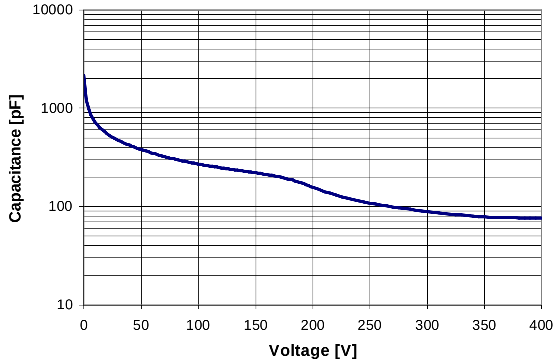

Figure 3: Capacitance vs. bias voltage.

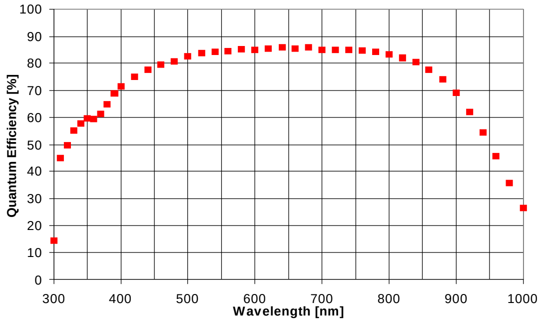

Figure 4: APD quantum efficiency.

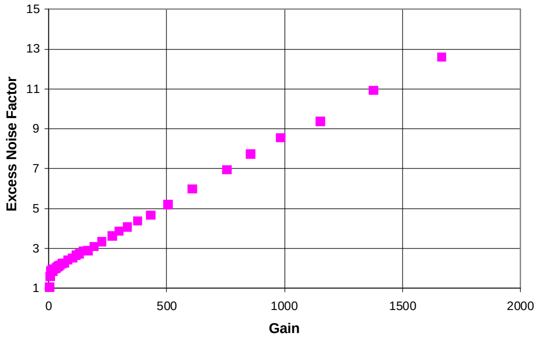

Figure 5: Excess niose factor vs. gain. Statistical fluctuation of the avalanche multiplication F=kM+(2-1/M)(1-k), where k is a ratio of the ionisation coefficients for holes and electrons and M is an APD gain, contributes to the constant term as sqrt($F/N_{p.e.}$)

B. *Stability*

The critical parameters of the photo detector, scheduled to run in the LHC experiment are the radiation hardness and the long-term stability. First, because both neutron and photon radiation levels will be rather high, second because the detectors will have to work several years practically without any maintenance and reparation.

The radiation hardness of APDs is tested in the 70 MeV proton beam of PSI. The beam rate is $9\text{x}10^{12}$ protons/cm^2, which is equivalent to $2\text{x}10^{13}$ of 1MeV neutrons/cm^2, a 10 years fluence expected in CMS barrel [3]. The dark current versus neutron flux for several APDs is shown in figure 6.

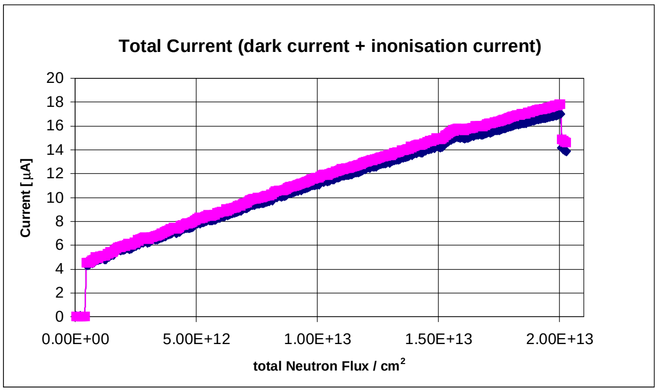

Figure 6: Total current for APD under Vr vs. neutron flux.

The rise of the dark current to 10-15 µA by 10 years will not degrade very much the overall ECAL performance. The breakdown voltage is decreased after irradiation by several volts, which is not dangerous because the operating to breakdown voltage distance is typically more than 30 volts. Several percents of APD during irradiation go quickly to the breakdown. This effect is under investigation now and is supposed to be removed before the mass production start. A new facility with a ^{252}Cf source is currently setting up in Minnesota University. Irradiation by “pure” neutrons at lower rates will give a complimentary information, very important for understanding of the nature of APD damage effects.

The long-term stability is tested during the accelerated ageing: keeping APD at 80°C under the bias corresponding to the gain=50 at this temperature. No significant degradation of the essential APD parameters was observed after 2 months ageing, corresponding to 10 years of operation under CMS ECAL running temperature of 18°C.

III. QUALITY ASSURANCE/CONTROL PROCEDURE

The scheme of the APD path from the Producer to the final capsule mounting is presented in Figure 7.

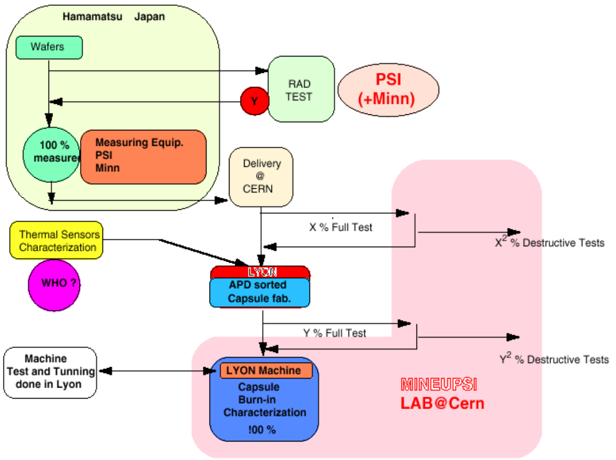

Figure 7: APD / capsule test

A small fraction of APD, 5 samples from each wafer, will be first packaged and sent to CERN where all parameters will be measured and after to PSI for the radiation hardness acceptance test. In case of negative result the corresponding wafer will be rejected. In case of positive – all APDs will be packed and tested at the Hamamatsu test bench, similar to ones installed at CERN and PSI. All APDs which meet the specification will be delivered to CERN where a certain fraction of them will be tested at the CERN APDlab test benches. In case of the significant deviation from the desired parameters, full lot or some wafers could be returned to Hamamatsu. Some fraction of APD will be placed to the oven for the accelerated ageing test.

A quality assurance facility installed at CERN APDlab is equipped with six computer-controlled set-ups to measure:

- gain as function of the bias voltage and temperature,
- capacitance versus bias voltage
- quantum efficiency and gain versus wavelength
- noise and excess noise factor
- timing response
- accelerated ageing.

All set-ups can run in parallel. The gain and quantum efficiency set-ups are equipped with the temperature stabilisation systems.

C. Gain set-up

The sketch of the gain set-up is shown in figure 8. The set-up includes the APD housing box, Keithley487 picoammeter/voltage source, Keithley7001 bipolar switch and Keithley485 picoammeter. The APD housing box consists of a water cooled aluminium plate to which a printed circuit board with 20 APDs mounted in ZIF sockets is attached. The plastic fibres of the light distribution system bring the light from the blue LED (Nichia NSPB 500S) to the APDs front window (figure 9).

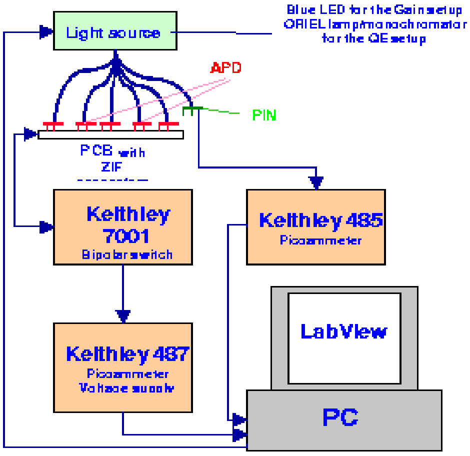

Figure 8: Sketch of the Gain measurement set-up

A PIN diode is mounted on one of fibres and is used to monitor the light intensity. A water from the Neslab RTE-211 chillier is pumped through the Al plate allowing the APD temperature to be held between 8 ant 80°C with 0.2°C precision. The APDs temperature is measured by the AD590 sensor.

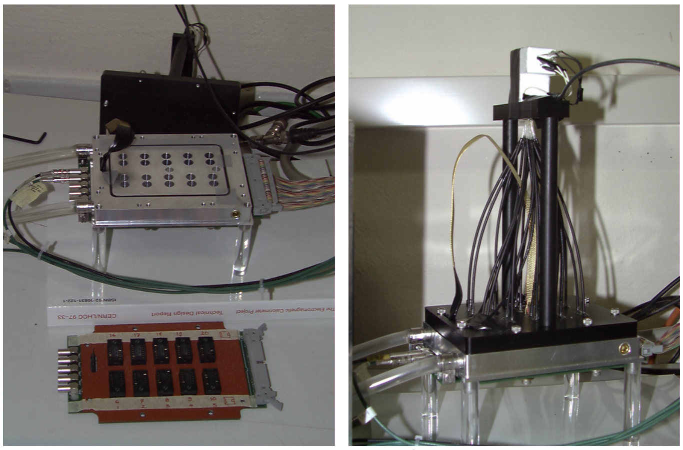

Figure 9: APD housing box of the Gain set-up

The APD bias and the current readout is provided by Keithley487 picoammeter/voltage supply coupled to twenty channel bipolar switch Keithley2001. The reference PIN diode is read out by the Keithley485. A PC running LabView controls all devices via GPIB interface. The gain curves measurement for 20 APDs is fully automatic and takes about 2 hours.

D. Capacitance set-up

The bench where capacitance and series resistance are measured consists of a HP LCZmeter 428A, a Keithley2410 picoammeter/voltage source and a Keithley2000 switch. Both parameters are measured as a function of bias voltage. The capacitance measurements are made at a frequency of 500kHz and take about 15 minutes per APD. The C(V) curves provide an information on the APD doping profile, which depend on the stability of the production technology and is an important parameter for the quality control and assurance.

E. *Quantum Efficiency set-up*

The Quantum Efficiency set-up is similar to the Gain one, except the light source is the ORIEL Na Lamp with the Cornerstone150 computer-controlled monochromator. It can provide the light in the 300-1020nm range in several nano-meters bin (depend on the output collimator width) with 0.5nm precision. The quantum efficiency is measured for the wavelengths from 340nm to 800nm with 10nm step. The APD bias is 10V(M=1). The measurement for 20 APD takes 3hours.

F. *Excess Noise Factor set-up*

Noise, excess noise factor nuclear counter effect and response APD to gamma-rays are measured in a set-up which consist of the universal APD-housing box, the Ortec142 preamplifier connected to the Ortec420 research amplifier. Signal and noise amplitudes are measured by the LeCroy 2259 ADC and the LeCroy 2249W QADC or by the Tektronix TDS 540 digital oscilloscope, which is used also for the noise spectra analysis. A Sr^{90} source is used for the nuclear counter effect measurement and the system is calibrated with a Hamamatsu 200µm thick PIN diode. Gain measurements are made with Fe^{55} and Am^{241} sources. All measurement on this set-up are made for the single APD and take, depending on the complexity, from 30 minutes to several hours

G. *Timing response set-up*

APD timing response is measured using the Tektronix TDS 540 digital oscilloscope. A 3ns pulse from VSL-337 UV laser is injected through a 200m long 100µm diameter quartz fibre. The APD response is measured directly at the 50Ω input of the oscilloscope.

H. *Accelerated ageing set-up*

APD long term stability is tested at the accelerated ageing set-up. The sketch of set-up is shown in figure 10.

The ageing set-up consists of two ovens, housing 5 printed circuit boards (PCB) with 80 APDs in ZIF connectors each. All boards are connected to the Keithley7002 switching system with ten 7011-C switching cards. Each PCB has two high voltage channels, connected to the CAEN SY-127 high voltage system with A333 HV cards, hence 40 APDs are biased by a single HV channel. APD current through the 100kΩ resistor is read out by the Keithely2000 voltmeter through the Keithley7002 switch. Two APDs are connected to one readout channel. The bias voltage and temperature are monitored using Keithley2000. PC running LabView controls the measurement procedure. APD currents are measured periodically, usually once per hour, and recorded to the local disk.

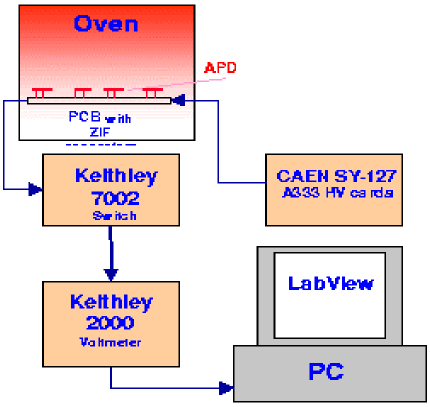

Figure 10: Sketch of the ageing set-up

The ageing slightly change the breakdown voltage, decreasing it for most of APDs by less than 1V. The dark current increases by about 1na. No change of the quantum efficiency, capacitance and other parameters where found. The changes, although well visible, are not significant and the accelerated ageing is considered as non-destructive.

Some APDs produced at the beginning of this year showed a sharply rising dark current after several days of the accelerated ageing at 80°C (figure 11). The problem, connected to the production technology, in particular etching of the groove, was localised and removed by Hamamatsu.

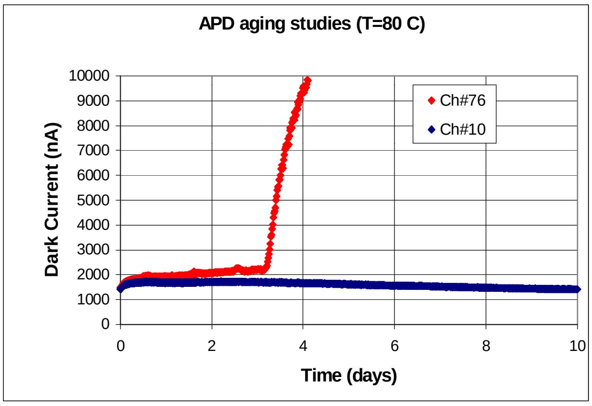

Figure 11: Current during accelerated ageing for good and bad APDs

IV. CONCLUSIONS

The Hamamatsu S8148 APD, developed for CMS ECAL detector, is well suitable for use in this detector. The stability and reliability issues are crucially important at the mass production stage. To coop with this challenge, CMS collaboration has defined an APD quality acceptance and test procedure and set-up at CERN a dedicated quality assurance/control facility. The facility consists of 6 computer controlled test benches and is capable to test during the mass APDs delivery to CERN:

Gain, dM//dV, dM/dT	100% of APDs
Capacitance, serial resistance	up to 20%
Quantum efficiency	up to 30%
Noise, excess noise factor	up to 5%

The big fraction of the tested APDs will be very useful at the beginning of the mass production and will be decreased to the foreseen by TDR 2-5% at the stable APD production phase.

V. REFERENCES

[1] The Electromagnetic Calorimeter Project, Technical Design Report, CERN/LHC 97-31(1997).

[2] A.Karar et al. Neucl. Instr. and Meth. 428A (1999), 413

[3] R. McIntyre, IEEE trans. Electron Dev. ED-19 (1972), 703.