Properties of the Most Recent Avalanche Photodiodes for the CMS Electromagnetic Calorimeter

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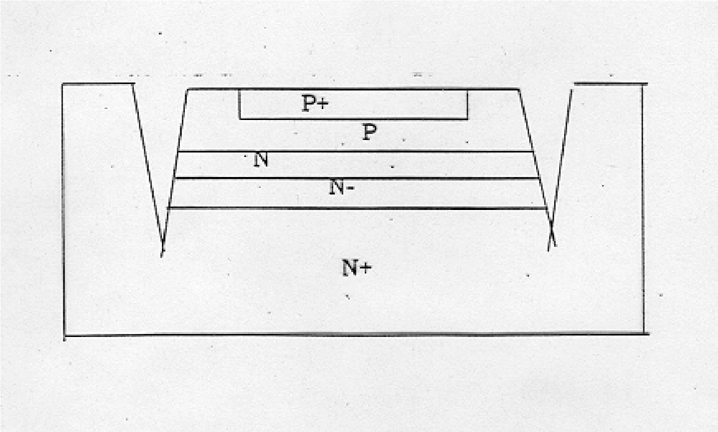
Avalanche Photodiodes (APD) with improved characteristics are being developed by Hamamatsu Photonics for the electromagnetic calorimeter of the CMS experiment. More than 30 prototypes have been made and investigated during the last 3 years in a development program, that showed significant progress. The parameters of the most recent APDs including the long term stability and the effect of a high radiation level with a neutron fluence of 2×10^{13} n/cm^2 have been studied and will be presented.

Structure of the selected APD type



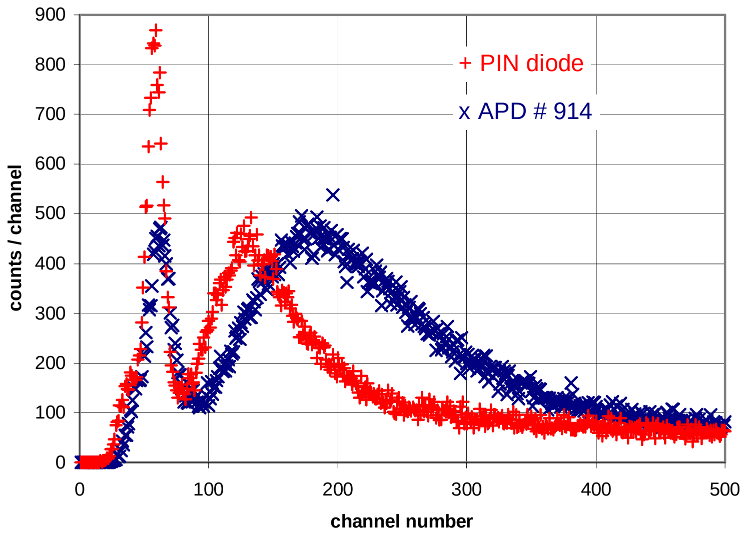
Parameters:	
area:	5x5 mm^2
operating voltage:	≈ 330 V
capacity:	70 pF
serial resistance:	3 Ω
dark current:	< 10 nA
dM/dV*1/M:	3.3 % /V @ M=50
dM/dT*1/M:	2.2 % /°C @ M=50
quantum efficiency:	70 % @ 420 nm

Hamamatsu APDs are produced by epitaxial growth on low resistivity N+ silicon, ion implantation and diffusion.

This type has a groove, which is some 30 micron deep and wide, to suppress the surface currents.

The layer of N- material was introduced to reduce the capacitance.

Nuclear Counter Effect



Response of a PIN diode and an APD to electrons from a ^{90}Sr source

We define an effective thickness, which is evaluated by:

$$l_{eff} = \frac{200\mu m}{(\text{peak position})_{PIN}} \times \frac{(\text{peak position})_{APD}}{M}$$

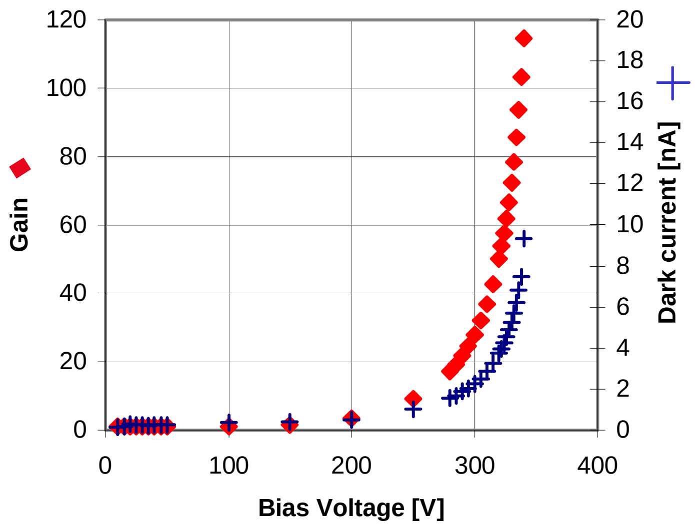
The PIN diode has a thickness of 200 micron.

M is the gain of the APD.

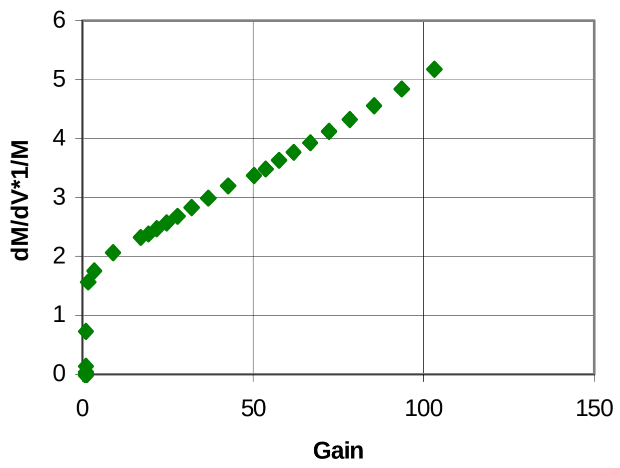
l_{eff} would be the thickness of a PIN diode, that would give the same ratio of the signal from a MIP to the signal from light created in the crystals as an APD will give.

APD # 914 has l_{eff} = 5.6 micron.

A MIP will cause a fake signal as big as the signal from a 112 MeV gamma ray (assuming a yield of 4 photoelectrons per MeV in $PbWO_4$).



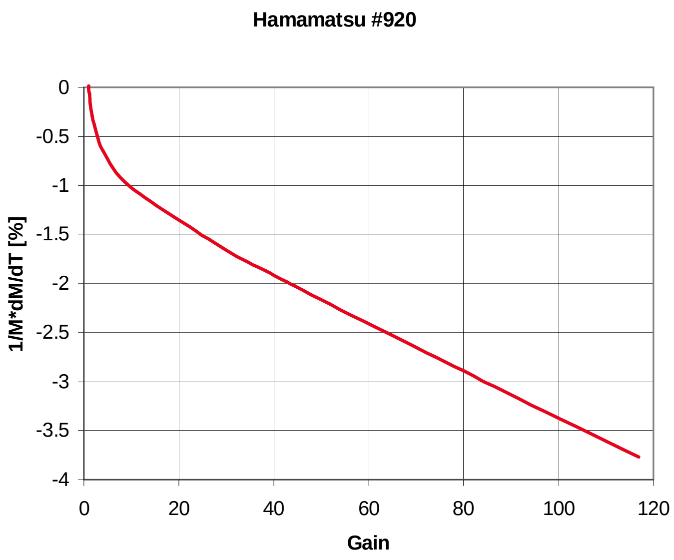
Gain and its stability



The gain is a steep function of the bias voltage. The variation of the most recent APDs (here Hamamatsu # 915) at gain M = 50 is:

$$\frac{dM}{dV} \times \frac{1}{M} = 3.3\ \%\ /V$$

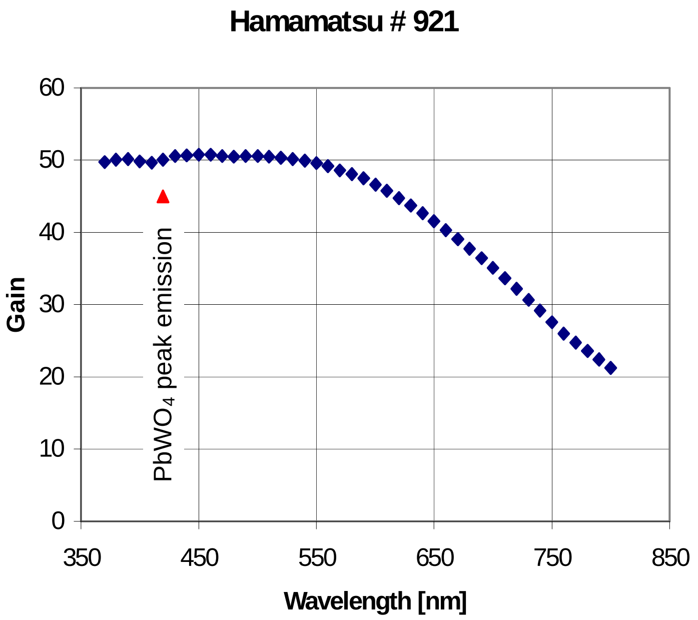
Temperature dependence of the gain of APDs

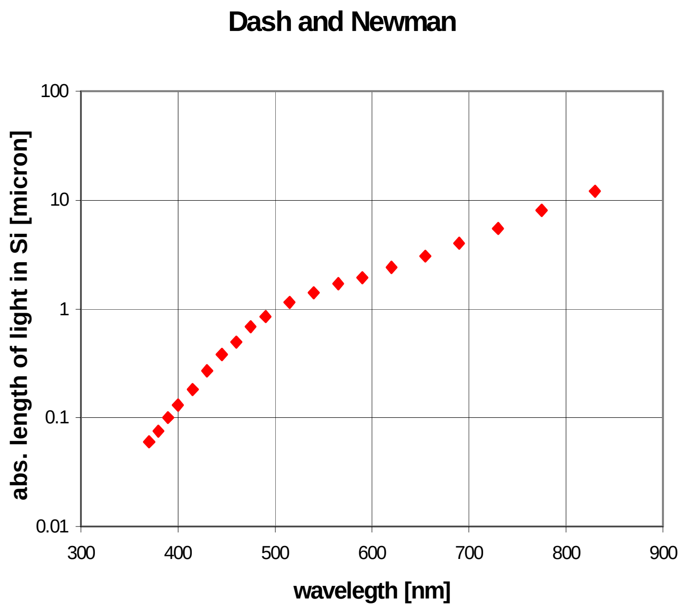


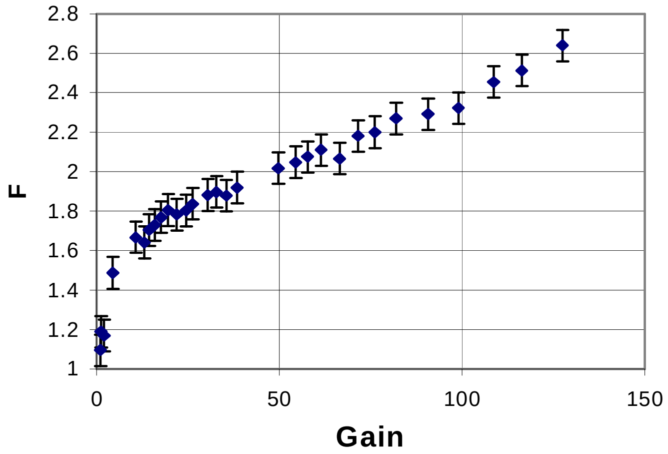
The gain of APDs depends on the mean free path length of the electrons and therefore on the temperature. For recent APDs we find a coefficient of -2.2 %/°C at gain 50.

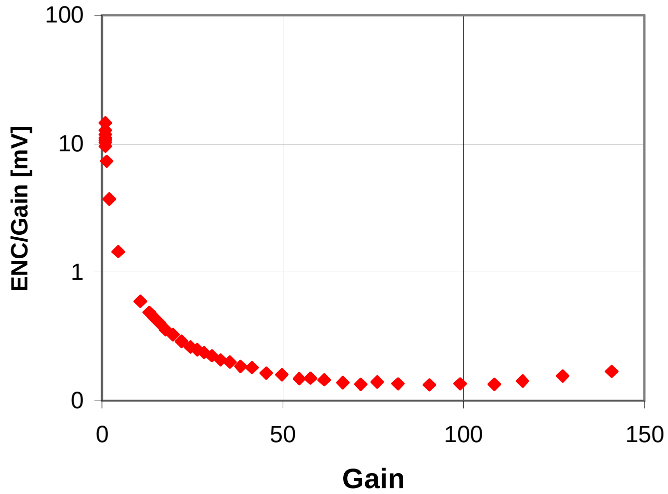
Unfortunately the $PbWO_4$ crystals have the same negative temperature coefficient. This forces us to stabilize the temperature of the calorimeter at the level of 1/10 of a degree.

The gain is a function of the wavelength: light with wavelength longer than 550 nm penetrates deep into the silicon and therefore electron-hole pairs are generated near or even behind the p-n junction, the amplification region.









Excess Noise Factor

The avalanche multiplication is a random process leading to additional fluctuations in the collected charge. These fluctuations are characterised by the excess noise factor F. At high gain F can be approximated by the expression:

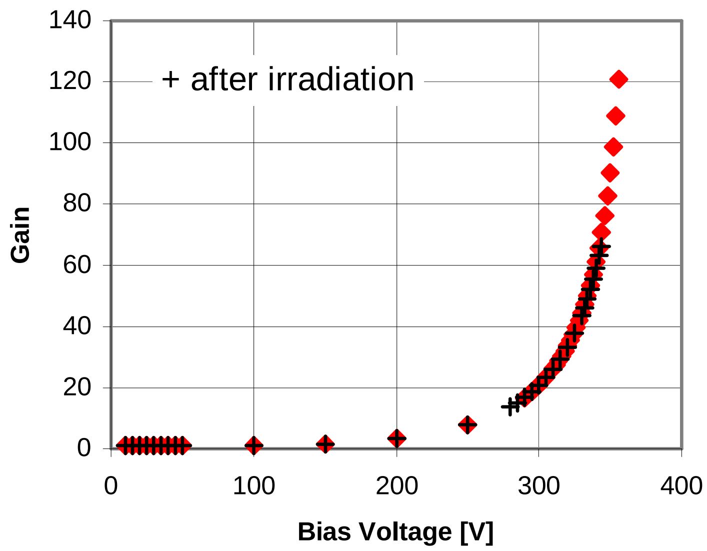
$$F = k \times M + \left(2 - \frac{1}{M}\right) \times (1 - k)$$

where k is the ration of the ionisation coefficients for holes and electrons and M is the gain.

The energy resolution then becomes:

$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}} \oplus \sqrt{\frac{F}{N_{pe} \cdot E}} \oplus \frac{Noise}{N_{pe} \cdot E} \oplus Const$$

Effect of irradiation



APD # 913 has been irradiated with $9x10^{12}$ protons/cm^2. Taking the proper nonionizing energy loss (NIEL) this corresponds to a total fluence of $2x10^{13}$ neutrons/cm^2, the fluence we expect in 10 years of LHC operation.

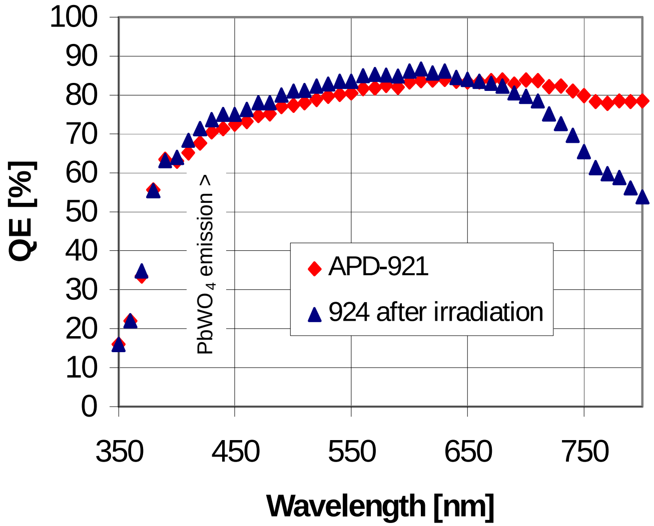
6 weeks after irradiation (the APD is not fully annealed - 20% of the defects have a lifetime of 600 days) the gain and the dark current have been measured:

The gain at 334 V is reduced by 3 % from 50 to 48.5. To obtain gain 50 APD # 913 now needs 335 V.

The dark current went up from 2.5 nA to 3990 nA (at 18 °C).

All other parameters are unchanged.

The quantum efficiency of APDs is not affected by irradiation



APD #924 has been irradiated with an equivalent of 2×10^{13} neutrons / cm^2

Irradiation with ^{60}Co does not change APDs with a protection layer made of Si_3N_4 (only the surface current increases slightly).

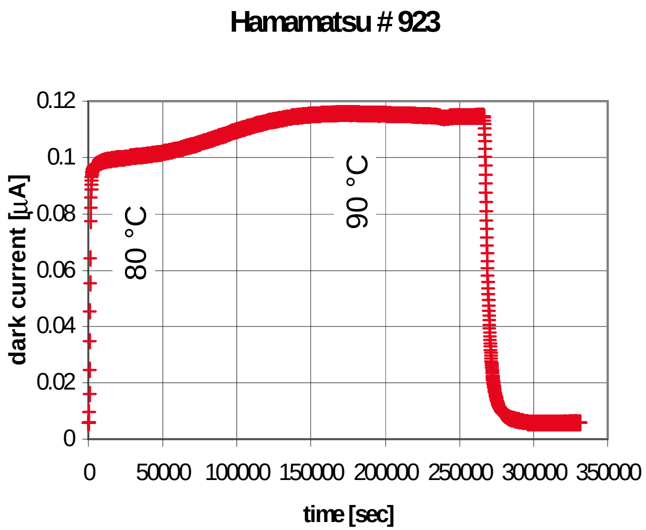
Irradiation with protons or neutrons creates defects and therefore the bulk current increases linear with the fluence.

The quantum efficiency is affected only at wavelength longer than 600 nm. The red and infrared light penetrates deep into the silicon, creates electron-hole pairs mostly behind the p-n junction, where the electrons see only a small electric field and recombine or get trapped by the defects.

Long term stability

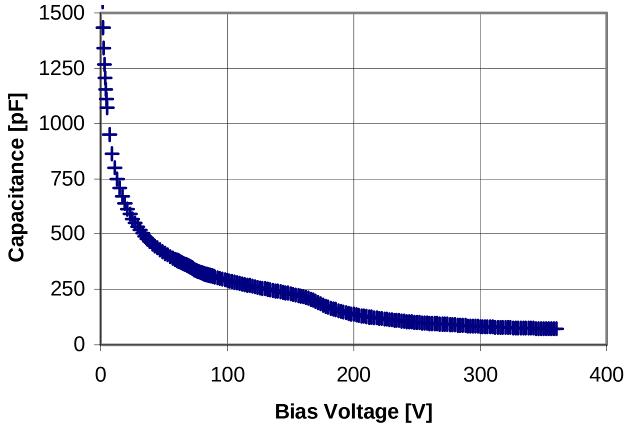
$$MTF_{T1} = MTF_{T2} \cdot e^{\left(\frac{E\cdot(T2-T1)}{k_B \cdot T1 \cdot T2}\right)} \qquad E = 0.52\ \text{eV}$$

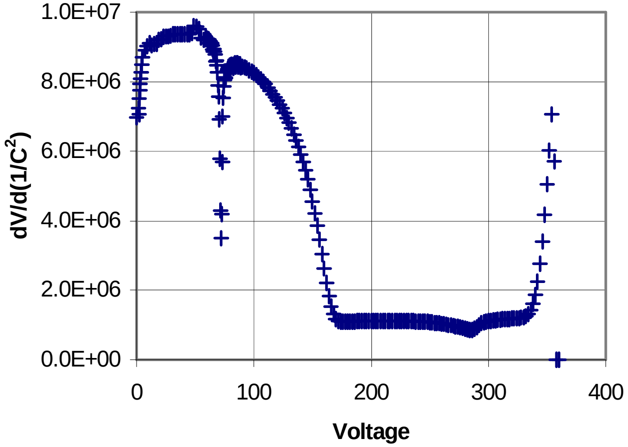
$$MTF_{18^\circ} = MTF_{90^\circ} \cdot 61 \quad \Rightarrow \text{ 3 days at } 90^\circ \approx \text{ 180 days at } 18^\circ$$



In order to test the Mean Time to Failure rate an APD was running at a bias voltage for gain 50 (at room temperature) in an oven at 80 °C and later on at 90 °C. After switching off the heating the dark current came back to exactly the same value, that had been measured before the heating.

A view into Hamamatsu's kitchen

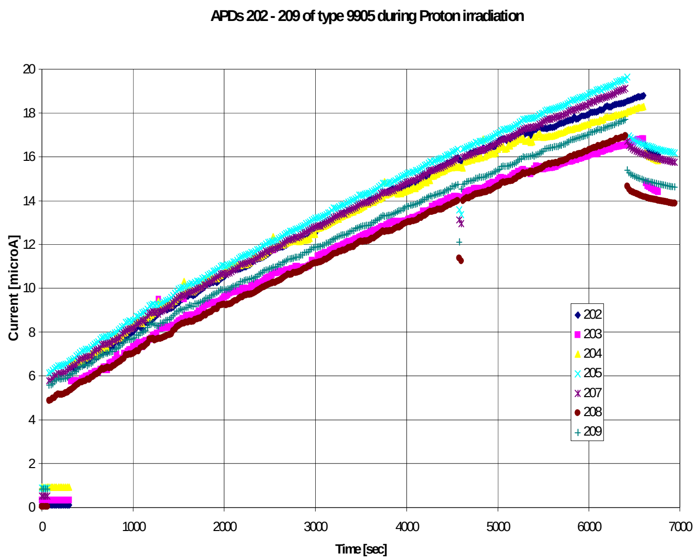


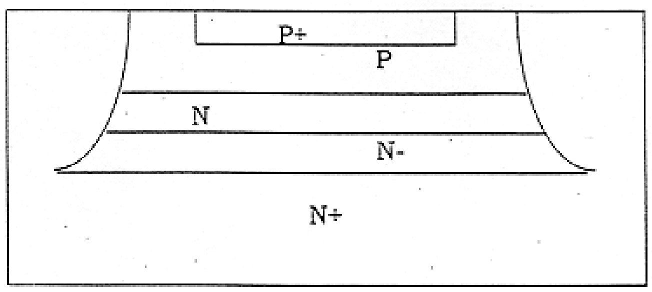


The capacitance of recent APDs from Hamamatsu with an area of 5x5 mm^2 have a capacitance of 70 pF when they are fully depleted (the example is # 921).

A plot dV/d(1/C^2) over the bias voltage shows the distribution of dopants in the APD (the capacitance is inversely proportional to the depletion width and the voltage needed to deplete a semiconductor is proportional to the dopant concentration).

New type of APD structure





This new type avoids the groove.

It has shown to be stable during the irradiation and promises to be very reliable.

The basic parameters are similar to the parameters of the type with groove.