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Radiation hard avalanche photo-diodes for the CMS detector

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Abstract

The avalanche photo-diodes, developed by Hamamatsu Photonics in collaboration with CMS, which are to be used to read out the lead tungstate crystals in the barrel part of the CMS electromagnetic calorimeter, are described. The procedures taken to ensure their long term reliability in the radiation environment expected in CMS are outlined, as well as the studies made to verify the very high reliability required.

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On leave from INR (Moscow)

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The avalanche photo-diodes, developed by Hamamatsu Photonics in collaboration with CMS, which are to be used to read out the lead tungstate crystals in the barrel part of the CMS electromagnetic calorimeter, are described. The procedures taken to ensure their long term reliability in the radiation environment expected in CMS are outlined, as well as the studies made to verify the very high reliability required.

Keywords: Silicon avalanche photodiodes; Calorimetry; Radiation hard; Screening
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1. Introduction and requirements

In the barrel part of the CMS ECAL, the light from 61,200 lead tungstate crystals will each be detected by a pair of Avalanche Photodiodes (APDs) [1]. The use of lead tungstate allows a fast, compact and radiation hard calorimeter, but has the disadvantage that the amount of light produced by the crystals is modest. The calorimeter is located inside a high field solenoid.

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The requirements for the photodetectors include operation in a 4 T field, radiation hardness at the level of 2.10^{13} n/cm^2 and 2.5 kGray, speed (□10 nsec), and of course compatibility with the demanding ECAL energy resolution requirements. The latter implies large area, good sensitivity to the light emitted by the crystal (430 nm peak), stability and insensitivity to voltage and temperature fluctuations as well as low capacitance, series resistance, noise and dark current. However, the low light yield of the crystals brings in two further important requirements: gain and insensitivity to ionising particles traversing the diode.

They must be reliable at the level of 99.9% after 10 years with the radiation in ECAL, and finally they must be affordable since 122,400 pieces are needed.

2. APD properties

The APDs were developed by Hamamatsu in close collaboration with CMS-ECAL and meet the above requirements. They are 5x5 mm square silicon photodiodes with a quantum efficiency of 75% at 430 nm, operated in avalanche mode to provide a gain of 50 at an operating voltage of ca 380 V. Incident photons are converted in a very thin layer at the surface and their electrons amplified by a high field p-n junction. Electrons from ionising particles traversing the diode are only amplified if produced in the conversion layer with an effective thickness of 6 μm.

The distance between breakdown and operating voltage is 45 ± 5 V (which allows gains of over 2000 in some cases). This has proved to be an important parameter in achieving the required radiation hardness. Before being passed for installation in CMS they are required to behave without problem up to gain 400.

Other characteristics of the APDs are described elsewhere [2-6].

3. Radiation hardness and stability

This APD has proven to be very robust and radiation hard. By radiation hard is meant that after receiving doses, typically double those expected in CMS, for most APDs no change in any electrical properties has been observed, with the exception of the unavoidable increase in dark current. Cooking in an oven under bias for a time equivalent to over 10 years at room temperature also induces no change in the characteristics. Even after dramatically higher doses were given to a few APDs they were found to be functional.

Nevertheless, a few per cent of APDs suffer or even die under irradiation or cooking – for example they may show a reduced value of the breakdown voltage (V_b) or an anomalously large dark current (I_d). In order to achieve the required reliability of 99.9% in CMS, all APDs are screened and the weak ones removed.

4. Screening

During development the standard irradiation used to test the APDs was 70 MeV protons with a dose equivalent to or in excess of that from the neutron and ionisation fluences expected in CMS. However, tests with ^{60}Co irradiation, followed by proton irradiation (after first being annealed) indicated a similar damage sensitivity – apart from the induced I_d which is much lower after ^{60}Co irradiation since there is almost no displacement damage in the silicon bulk. On the other hand irradiation with low energy neutrons (ca 1 MeV), while inducing the large dark currents, does not induce other damage to the APDs. Thus the damage causing unreliability is done by ionisation at the surface. Hence it was decided to screen all APDs by irradiation with ^{60}Co followed by cooking, acting as an extended burn-in. The cooking also anneals the I_d induced by the irrradiation, on average by a factor of 6, to values negligible for CMS.

In detail the screening procedure developed is as follows:

1. 5 kGy of isotropic ^{60}Co irradiation in 2 hours.
   After 1 day measure I_d to breakdown.
   After 1 week measure the noise at gain 1, 50, 150 and 300.
2. Cook at 80 °C for 4 weeks under bias at 350V
   Measure I_d to breakdown.

After this the good APDs are selected, paired by operating voltage and mounted in “capsules” to be glued to the crystals. As a final step in the screening, the noise from each pair is then measured. The irradiation is done at PSI, the cooking at the APD lab at CERN, and the capsule production in Lyons.

APDs are rejected if after irradiation or cooking V_b has changed by more than 5V, or if I_d or the noise is anomalously large (see Fig 1). The cuts are applied relative to the mean for the wafer, due to large wafer-to-wafer variations in the I_d and the noise, and to accommodate measurement offsets in V_b.

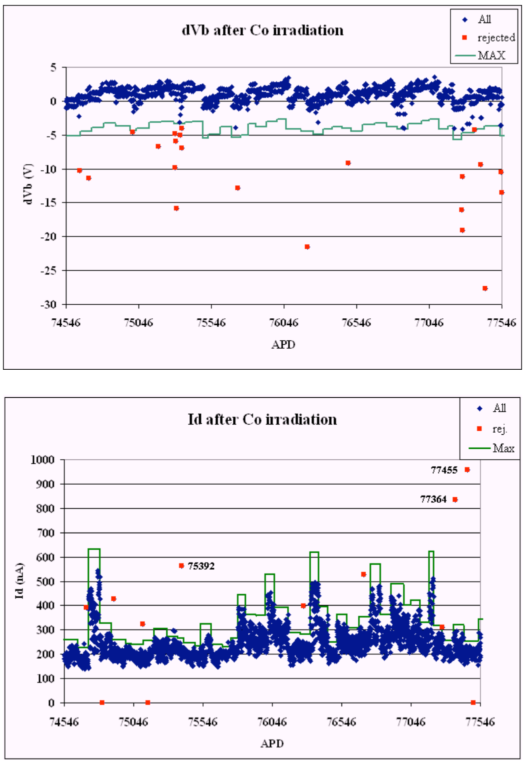

Fig. 1. Change in breakdown voltage (dV_b) and induced dark current (I_d) after irradiation, for 3000 APDs. The lines mark the rejection cuts, set for each wafer

APDs are also rejected if the ratio I_d/M rises between M = 50 and 400, where M is the gain. If I_d is due to surface currents, it will rise with bias voltage ohmicly, and thus fall steadily with M. A rise in I_d/M well below the normal breakdown point could come from current at a local defect being amplified. Fig 2 shows I_d/M *vs* M after irradiation for APDs from one wafer where most are well behaved but three are rejected due to rises in I_d/M well below M=400.

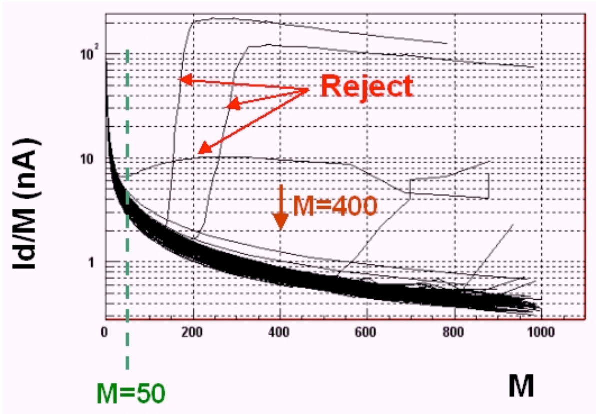

Fig. 2. I_d/M *vs* M for APDs from one wafer. For good APDs I_d/M does not rise between M=50 and M=400.

5. Reliability of screening

The screening procedure was empirically determined, initially in comparison to the effects of proton and neutron irradiation. However, the radiation dose is double the maximum expected in CMS and the cooking corresponds to about 4 years of accelerated aging. In order to tune the screening procedure and the cuts applied to obtain effectiveness (rejection of all weak APDs) and efficiency (no excessive rejection of good APDs) a number of APDs were screened twice.

The idea of these double screenings is that if the screening is effective, all weak APDs are found in the first screening and no new ones will be found in the second one. If the screening is efficient, a large fraction of APDs found weak in the first screening will again be weak in the second screening. In tuning the screening, priority was given to effectiveness.

The sample of APDs used for the double screening tests was deliberately biased to have a much larger proportion of weak APDs than a normal sample so that the cut boundaries and effectiveness could be explored. The studies were also used to determine the final technical specification to Hamamatsu, but the results presented here are only for APDs conforming to the final specification. APDs from positions on wafers with known mask defects are excluded. The noise measurements were not included in these screenings.

The results of the double screening are that:

- For 834 APDs which passed the first screening, only 1 failed the second screening, implying a reliability around the required 99.9% level. A further 12 failed a strict application of the cuts but were very close to the (arbitrary) border and would be expected to be reliable in CMS.
- For 221 APDs which failed the first screening, 102 (46%) also failed the second screening.

The one APD which failed the effectiveness test had an I_d/M curve which started to rise at M=170 after the second irradiation (see Fig 3). But there was no change in V_b nor an anomalous I_d after either the second irradiation or cooking. The I_d/M curve was normal after the second cooking. It is expected that such an APD might become noisy in CMS, but not die.

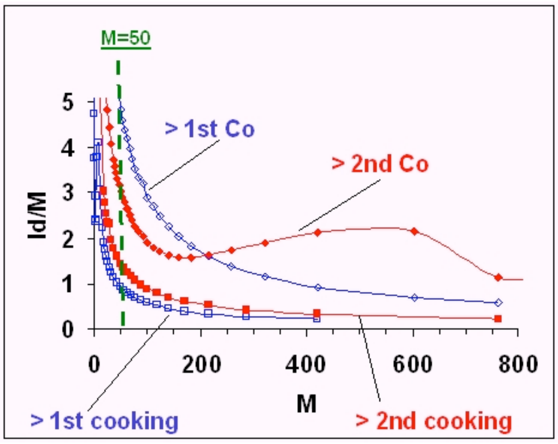

Fig. 3. I_d/M *vs* M at each stage of the screening for the APD which failed the double screening test.

An additional result, which may not have a direct consequence for the APDs' reliability, is the behaviour of I_d at M=50. The induced I_d after the second irradiation is on average only half that after the first irradiation, while after the second cooking it is typically 30% larger than after the first cooking. This can be seen for one APD in Fig 3. A possible explanation is that the extended burn-in anneals away some faults in the new APDs so that less current is induced in the second irradiation, while each irradiation creates a small amount of permanent damage, which is not annealed by the cooking. Similarly, weak APDs whose V_b was lowered in the screening tended to have smaller changes in V_b after the second irradiation, but larger ones after the second cooking.

6. Conclusions and status

The APD developed for CMS-ECAL is a very robust, radiation hard device; under LHC conditions it is expected to develop a dark current equivalent to about 50 MeV of noise per pair on a crystal [1], but no other properties are expected to change, after 10 years.

A screening procedure has been developed which is used to remove about 5% of the APDs. Double screening tests indicate that, provided the results translate to CMS conditions, the APDs installed in CMS should be reliable at the required 99.9% level.

The delivery of APDs by Hamamatsu and their screening by CMS-ECAL are on schedule.

Acknowledgments

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