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Double Screening Tests of the CMS ECAL Avalanche Photodiodes

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Abstract

Specially developed avalanche photo-diodes (APDs) will be used to measure the light from the 61,200 lead tungstate crystals in the barrel part of the CMS electromagnetic calorimeter. To ensure the reliability over the lifetime of the detector, every APD is screened by irradiation and burn-in before it is accepted for CMS. As part of the establishment of the screening procedure and to determine its effectiveness, a large number of APDs were screened twice. The results of these tests suggest that the required reliability will be achieved.

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

The Compact Muon Solenoid [1] detector (CMS) will be one of the two general purpose detectors installed at the 14 TeV proton-proton collider LHC under construction at CERN. The Electromagnetic Calorimeter (ECAL) of the detector will be a hermetic full energy calorimeter [2] made of 61,200 lead tungstate ($PbWO_4$) crystals mounted in the central “barrel” part, closed by 7,324 crystals in each of the two end-caps. The ECAL will be mounted inside the superconducting coil of a 4 Tesla solenoid. The use of lead tungstate crystals leads to a compact calorimeter but the low light yield of this crystal requires that the light sensors have gain. In the barrel part the light emitted by each of the crystals will be measured using two avalanche photodiodes (APDs) and in the end-caps with vacuum phototriodes. The aim of the CMS ECAL is to measure the energy of photons (and electrons) with as good resolution as possible, with the goal of 0.67% rms at 100 GeV. The operating conditions at the LHC, with large numbers of particles entering the detector every 25 nsec, require that the ECAL components be fast and radiation hard. After the ECAL is installed it will not be practical to replace faulty APDs and so reliability is very important, the goal being to have at least 99.9% of the APDs still operational after 10 years of running in CMS.

The APDs to be used in the CMS ECAL have been specially developed to meet these requirements by Hamamatsu Photonics, in close collaboration with the APD group of ECAL. They are silicon photodiodes operated in avalanche mode to provide a gain of 50 at an operating voltage of 340 – 440 volts. Breakdown voltage (Vb) is 45 ± 5 V above operating voltage, which provides a substantial safety margin, although in practice no change in Vb is expected during CMS operation. The 5x5 mm square sensitive area is covered with a thin silicon nitride passivation layer and a protective cover of epoxy resin. Before irradiation the dark current (Id) at gain 50 is typically around 3 nA. Other characteristics of the diodes are described in more detail elsewhere [3-5].

Radiation testing has shown that most APDs suffer no significant change in optical or electrical properties under irradiation, with the exception of the unavoidable increase in dark current. APDs given higher doses than those expected in CMS are usually still functional. The results of long term tests running APDs both at room temperature and in an oven also indicate that the diodes are intrinsically very stable. Thus the APD developed for CMS is basically a very robust device.

However, a few per cent of the APDs do suffer deterioration of their properties under irradiation – they may have reduced Vb or very large induced Id or they may become noisy. Occasionally APDs become inoperable. Hence in order to achieve the desired high reliability, it was found necessary to screen every APD for radiation hardness.

Similarly, running APDs in an oven for a few weeks also induces damage in a few APDs, although if they have previously been irradiated the number of new weak APDs found is very small. Running the APDs in the oven provides an extended burn-in test and also simulates aging in an accelerated fashion. Whether the damage experienced by some APDs is due the exposure of defects by extended running or to an aging-like process has not been determined. Nevertheless running the APDs in an oven constitutes a further reliability test and is thus used as the second step of the screening of all APDs; this also reduces the Id induced by the irradiation (typically a few hundred nA) by a factor of 6 in the standard APD screening procedure.

But initially a screening method had to be developed and shown to be effective. Since no clear boundaries between good and weak behaviour were found, this was not straightforward. To help establish and verify the effectiveness of the screening procedure, a number of APDs were screened twice. The results of these double screenings are reported in this paper. The primary goal of this work was to show that the screening used in the production of APDs for CMS reliably rejects weak APDs, but it was also important to verify that it does not waste an unacceptably large number of good APDs. The results also helped to refine the screening rejection criteria so as to achieve these goals and to establish the final technical specifications. A summary of these results has been published elsewhere [6].

2 Screening

During 10 years of CMS running the APDs will be subjected to ionising doses of up to 0.7 kGy, mainly from minimum ionising particles, and fluences of up to 2.10^{13} neutrons/cm^2, of mean energy about 1 MeV; the uncertainties on these estimates are thought to be up to a factor of 3 [7]. In the development phase the radiation hardness of prototype APDs was routinely checked using 70 MeV protons from the PSI Injector cyclotron, which quite closely simulate both the ionising irradiation and the hadronic damage to be experienced in CMS. But the large dark currents induced in the APDs by the hadronic damage to the bulk of the silicon renders them unsuitable for use in CMS afterwards. Thus such testing (or with neutrons) could not be used to screen all APDs to be installed in the detector. However, there was indication that the anomalous damage induced in some APDs by proton irradiation was in the surface region, not in the bulk of the silicon. Irradiation with gammas from a ^{60}Co source revealed weak APDs with a sensitivity similar to proton irradiation. This suggested that screening with gamma irradiation, which induces negligible damage to the silicon bulk and only moderate dark currents could be used effectively. The results of irradiating APDs with neutrons appeared to confirm this: such APDs developed large dark currents from damage to the bulk of the silicon but did not suffer big changes in Vb. These studies are reported in detail elsewhere [8].

The procedure used to screen each APD for radiation hardness and reliability was developed empirically, based on the experience of testing APDs during their development outlined above, and adjusted after the work reported here and other tests. The procedure finally adopted was the following:

1. Irradiate each APD mounted in conducting foam inside an isotropic ^{60}Co source, with 5 kGy in 2 hours.
2. After 1 day measure Id to breakdown.
3. After 1 week measure the noise at gains of 1, 50, 150 and 300.
4. Run the APDs under bias at 350V for 4 weeks at 80 °C.
5. Measure Id to breakdown.

The radiation dose is more than twice the maximum expected (including the factor of 3 for safety) in CMS, while the time in the oven is equivalent to an accelerated aging of 3.5 years, using the Arrhenius model [9]. Step 2 was carried out after 1 day to reduce the sensitivity to the initial fast self-annealing. APDs which pass the screening are then mounted in pairs in capsules to be glued on the crystals, and as a final step the noise of each pair is measured. In addition a small sample of screened APDs were sent to the University of Minnesota to be irradiated with neutrons to monitor the effectiveness of the screening in removing weak APDs. Steps 1 and 2 were carried out at PSI, steps 3-5 at the APD lab at CERN and the capsule production and testing in Lyon. Further details of the procedures are described elsewhere [5,6,8].

APDs are rejected if after either irradiation or after the extended burn-in they have a change in Vb of more than 5 V, or if the Id or noise are anomalously large. The cuts are applied relative to the mean values for all APDs from the same wafer to accommodate small measurement offsets in Vb, and because there are large wafer-to-wafer variations in the average Id and noise. The cut on Id after irradiation was set at 3 standard deviations but at least 100 nA above the wafer mean; after the burn-in the cut was 4 standard deviations but at least 30 nA above the wafer mean. APDs are also rejected if the ratio Id/M rises more than 10% between M = 50 and 400, where M is the gain. If Id is due to surface currents, it will rise ohmically and thus Id/M will fall steadily with increasing M. Such rises in Id/M are often but not always associated with a reduced value of Vb or large Id at M=50.

In addition it was found that many APDs from particular positions on the wafer failed the screening tests. Inspection by Hamamatsu Photonics of early deliveries indicated that this could be due to a faulty production mask at these positions. Hence if in one Lot more than 30% of the APDs from a wafer position failed the screening, all APDs in that Lot from this so-called “Bad Position” were rejected.

Finally, it was found that APDs conforming to the initial technical specifications, but with (Vb-Vr), the distance between breakdown and operating voltage, Vr, somewhat lower than normal, or with a rising Id/M curve measured by Hamamatsu before delivery, often failed the screening.

3 Concept and Goals of the Double Screening

As already mentioned, various tests and mistreatments have indicated that the APD developed by Hamamatsu is basically a very robust device. Thus the causes of the weakness of some APDs are probably small defects induced in the manufacture, whose origins and occurrence would be quasi-random. If the screening procedure is thorough – that is it finds every weak diode – then subjecting the diodes to the same procedure a second time would find no new weak ones. Any APDs only failing the second screening would indicate an ineffectiveness of the screening.

Most APDs which fail the screening test after the irradiation appear to have fully recovered after the extended burn-in. The failure of such an APD in the second screening shows that it is nevertheless still weak. Thus the second screening can also be viewed as a test of the meaningfulness of the screening procedure. If only a few such APDs failed the second screening it could suggest that the screening should be viewed more as a “curing” procedure for surface defects than as an efficient selection procedure; it could also result from too stringent criteria which would need adjustment. But if a large proportion of APDs which failed the first screening also fail the second screening, the procedure can be viewed as meaningful and efficient in the sense of not rejecting an undue number of good APDs.

Thus the goals of these tests were first, and most importantly, to indicate that the screening is effective and efficient - thorough in finding weak APDs but not rejecting an undue number - and secondly to adjust the criteria used to reject APDs to achieve this. In addition, at the time these tests were carried out, the final technical specifications for the APDs delivered by Hamamatsu had not been fixed and the results helped in determining what these should be.

4 Procedure and APD Selection

The screening procedures used in these tests were similar to those finally used in the screening of the APDs described above, but because they were carried out at an early stage of the production they were not identical. Routine noise measurements were not available. For some APDs the burn-in was at 90 °C for 2 weeks instead of at 80 °C for 4 weeks, with some mounted in conducting foam instead of being run under bias. Also, the analysis after the second screening had to be adapted as described in the next section.

The APDs were taken from the first 17 Lots delivered in the first half year’s production in 2001. Of the total 1276 APDs, 491 were quasi-randomly selected. The other 785 APDs were most of those from the last seven Lots delivered in 2001 which had failed the very tight provisional screening limits then being applied, plus 31 selected to explore the rejection criteria. The total sample provided a sufficient number of APDs to determine whether the effectiveness of the screening approached the desired value, but also enough weak APDs to examine the rejection efficiency. There were many APDs which marginally failed the provisional screening limits, which helped establish the final limits, and similarly there were a number with characteristics outside the final technical specifications and which helped to set these.

After the initial selection, a few APDs which had large Vb changes after the irradiation and after the burn-in were removed from the sample, being considered irrevocably dead. A further few APDs where the measurement data appeared suspect were also discarded.

The second screenings were carried out 2-3 months after the first screening, for the quasi-randomly selected APDs and about 7 months after the first screening for the APDs rejected in the initial screening of the last seven Lots. Between screenings the APDs were stored in conducting foam at room temperature.

It is important to point out that because of the bias of the selection in favour of weak or bad APDs, the failure rate reported here is much higher than in the production screening, where it is around 5%.

4.1 APDs irradiated under bias

As part of the double screening tests it was found that if the APDs were under bias during the first irradiation, they all failed the second screening tests. Since the APDs to be installed in CMS have all been irradiated mounted in conducting foam, this phenomenon is not of direct relevance to the main purposes of these studies and these results are presented separately in Section 8.

5 Analysis

In order to make the results presented here as relevant as possible to the APDs to be installed in CMS, the data were analysed using the final screening criteria and technical specifications. The basic logic of the analysis was straightforward: the results of both screenings for each APD were examined independently to determine whether it had failed either. The results were then categorised as: failed first screening only, failed both screenings, or failed second screening only. The detailed procedure, however, was slightly more complicated.

The results for the first screening were taken from the analysis used for the production screening of all APDs (see section 2, but without the noise measurements). In the second screening, the wafer mean values of dVb and Id were not available since typically only a few APDs from any wafer were used in these tests. Thus, for the second screening, the cut on dVb was set to 5V absolute, while for the induced dark current the ratio of that induced in the second to that induced in the first screening was considered as an additional indicator of weak behaviour. In practice this introduced very little ambiguity in the results. Similarly, the concept of a Bad Position, based on the analysis of all APDs from each Lot, was not relevant for the second screening. Finally 382 APDs were measured only one year after the second burn-in. These showed on average a reduction in Id of 28 % compared to 372 APDs from the same wafers which had been measured promptly. Of the 382 measured late, 72 (19%) failed the screening after the second burn-in compared to 56 (15%) of the 372 measured promptly. These APDs have therefore been included in the samples.

The APDs (delivered under the provisional specification) outside the limits of the final technical specification have been removed from the main sample and their results are presented separately. These APDs either had too small (Vb-Vr) or had Id/M rising for M < 400 in the measurements of Hamamatsu before delivery.

The APDs from the Bad Positions have also been considered separately and subdivided into two classes. For most Bad Positions there was no examination of rejected APDs by Hamamatsu and so the origin of their weakness was not determined. However, inspection by Hamamatsu Photonics of APDs from wafer positions labelled B09, D07, E10, F07 and K09 from some of the first 12 Lots delivered had indicated that they were weak because of production mask faults. These five have here been considered as Bad Positions in all these 12 Lots independently of the screening results, and APDs from them have been analysed as a separate class. From the 13th Lot onwards, pellicular masks were used and this problem was cured.

6 Results

Figure 1 shows typical results after the first irradiation. Figure 1a shows the change in Vb after irradiation, together with the limit of 5V with respect to the wafer mean. Figure 1b shows induced dark currents (at gain 50), similarly with the limits set for each wafer shown.

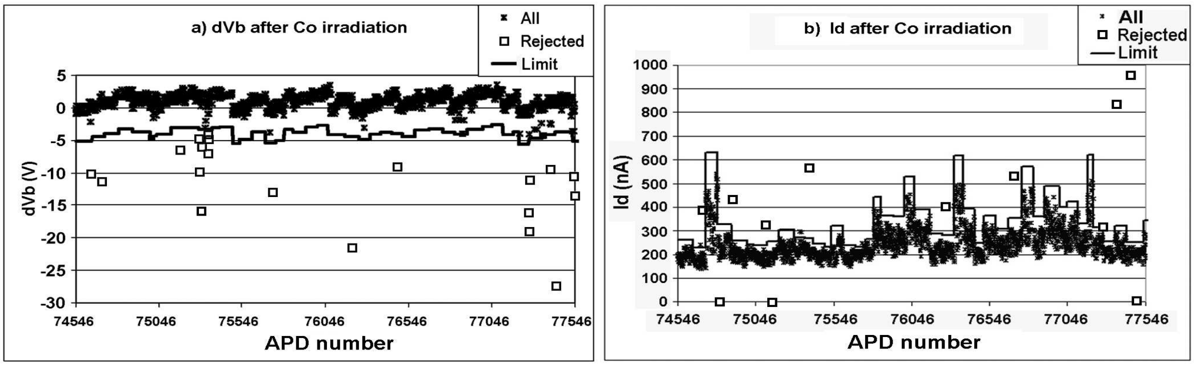

Fig 1. a) Change in breakdown voltage and b) induced dark current at gain 50 after the first irradiation, for 3000 APDs. The lines mark the acceptance limits, set for each wafer. The open squares indicate rejected APDs. The three APDs with zero dark current could not be operated at gain 50 due to a large reduction in Vb.

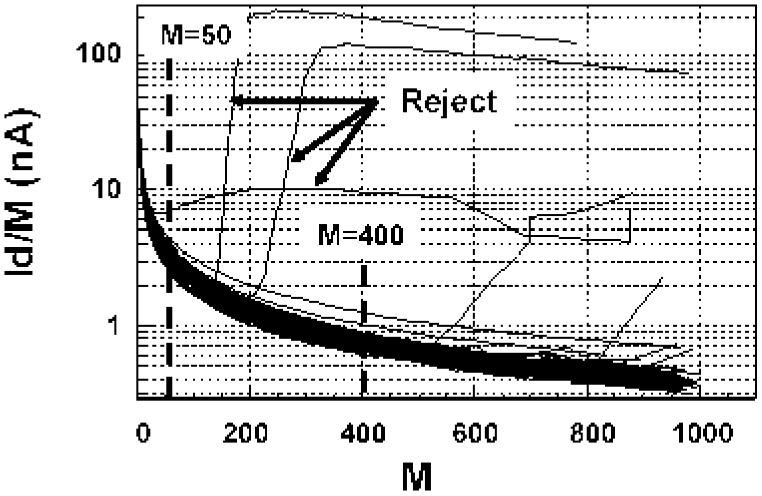

Fig 2. Id/M vs M curves for 126 APDs after the first Cobalt irradiation. For good APDs Id/M does not rise between M=50 and M=400.

Figure 2 shows the ratio Id/M plotted against M after irradiation for APDs from two wafers: for good APDs the ratio falls steadily to gains over 400, while for some APDs it shows a strong rise at lower gains.

The general trends in the dark current development for good APDs, through the four steps of the screening, will be discussed in section 7. For weak APDs, there was a tendency for a type of weak behaviour seen in the first screening to show up in a similar way in the second screening, but not always: in general the correlation between the behaviour of Vb and Id for weak APDs after each stage of the screening was not high enough to make reliable predictions.

6.1 The main sample

The main sample of 946 APDs consisted of the full selection described above, excluding the APDs which were outside the final specification (sect 6.2) or were from wafer positions considered bad (sect 6.3). The results are summarised in Table 1. Nearly half the APDs failing the first screening also failed the second screening, suggesting that the screening is not excessively wasteful in rejecting APDs. But of the 779 APDs passing the first screening, 12 (or 1.5%) failed the second screening on a strict application of the cuts, apparently not consistent with the desired goal of 99.9% reliability. However, all but 1 of these failures was marginal and may be considered unlikely to be relevant to the operation of CMS:

	Passing S1	**Failing S1**
Total	779	167
Passing S2	767	87
Failing S2	12	80

Table 1. Results of the double screening test for the main sample of 946 APDs. S1 and S2 represent the first and second screening respectively.

- 2 APDs had Id/M curves starting to rise at M=380 compared to the (arbitrarily set) limit of M=400.
- 1 APD showed a change in Vb of 5.4 V after the second irradiation compared to the limit of 5.0 V and showed no weakness after the second burn-in.
- 8 APDs were flagged because their Id after the second irradiation was about the same as after the first irradiation, compared to the more usual reduction to around half. The significance of this is unclear but none of the dark currents was particularly high and all these APDs looked normal after the second burn-in.

The APD which showed a clear violation of the second screening showed a rise in Id/M at M=170 (see Fig 3) after the second irradiation, but with no change in Vb and normal Id at gain 50, but it behaved well after the second burn-in. This indicates that if installed in CMS this APD would be operational at gain 50, but would possibly become noisy.

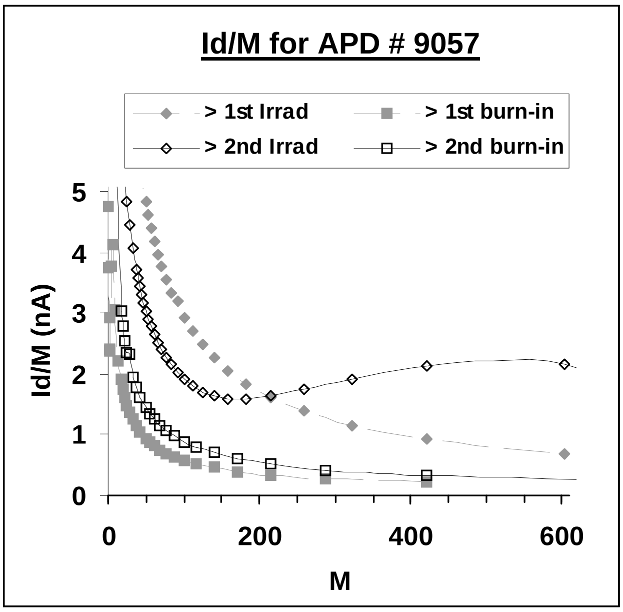

Figure 3. Id/M vs M at each stage of the screening for the APD which failed the double screening test.

6.2 APDs outside final technical specification

Table 2 summarises the results for APDs which were outside the final technical specification, either because (Vb-Vr) was too small (between 35 and 37 V) or because the Id/M vs M curve of Hamamatsu was rising, or both. Of the two diodes which failed the second screening only, one had an Id/M curve which turned up at M=350 after the second burn-in and the other had a rather high Id (600 nA) after the second irradiation but recovered in the second burn-in.

The overall failure rate (65%) for these APDs, even allowing for the bias towards weak APDs in the sample, shows that tightening the technical specifications by raising the minimum (Vb-Vr) by 2 V and requiring a well-behaved Id/M curve were important improvements to the quality of the delivered APDs. On the other hand, the marginal failure of 2 APDs (1.3%) in this double screening test is similar to the results for the main sample. Thus although the sample is relatively small, such APDs also appear to be removed effectively by the screening procedure, if weak.

Reason outside final technical specifications	Number of APDs	Pass S1 & S2	Fail S1 only	Fail S2 only	Fail S1 & S2
(Vb-Vr) low and Id/M bad	15	3	3	0	9
(Vb-Vr) low	56	19	9	1	27
Id/M bad	85	32	10	1	42
Total outside specifications	156	54	22	2	78

Table 2. The screening results for APDs outside the final technical specifications.

6.3 Bad Positions

The sample of APDs labelled as coming from Bad Positions naturally has a high population of weak APDs since these are the reason the position is labelled bad. This sample is further divided into those APDs coming from positions where APDs were sent to Hamamatsu for inspection and evidence for a mask fault was seen (B09, D07, E10, F07 and K09) and those from other positions, labelled bad because over 30% of APDs from them in a given Lot failed the first screening.

Table 3 gives the results for the 109 APDs from Bad Positions with those from the five faulty mask positions excluded. The single APD passing the first screening but failing the second screening had an Id after the second irradiation similar to that after the first (rather than the usual reduced value), but behaved well after the second burn-in – i.e it showed the same behaviour as the 8 such APDs flagged in the main sample and its apparent weakness may be considered insignificant.

	Passing S1	**Failing S1**
Total	55	54
Passing S2	54	32
Failing S2	1	22

Table 3. Results of the double screening test for the sample of 109 APDs from Bad Positions excluding those from wafer positions B09, D07, E10, F07 and K09.

The results for the 65 APDs from the five positions with evidence for a mask fault are given in Table 4 and are strikingly different. First, *all* APDs failing the first screening also failed the second, rather than around half. But worse, 40% (18 out of 44) of the APDs passing the first screening failed the second one, and clearly failed it in all except one or two cases. Of these 18 APDs, 13 failed on the second irradiation with Id/M curves starting to rise between M=30 and M=90, and half had a high Id (one over 2 μA and one at 1.5 μA), while the remaining 5 had Id/M curves starting to rise between M=60 and M=340 after the second burn-in. Of the 13 APDs which failed the second irradiation, 11 recovered in the second-burn-in, but 2 were bad after each step. Finally, many of the failing APDs came from Lots other than those from which the samples had been sent to Hamamatsu for inspection, and a number were from the last Lot delivered before the introduction of the pellicular masks.

	Passing S1	**Failing S1**
Total	44	21
Passing S2	26	0
Failing S2	18	21

Table 4. Results of the double screening test for the sample of 65 APDs from wafer positions B09, D07, E10, F07 and K09 before the introduction of pellicular masks.

Unfortunately some APDs from these wafer positions where mask faults were apparent passed the production screening and will be installed in CMS. However, there were only 4 of the 62 APDs in this test which showed a big reduction in Vb after the second screening, and these showed this weakness unambiguously already in the first screening. Further, although all the APDs from these positions in the first 12 Lots may be considered potentially unreliable, there is no proof that the faults were present in them all. Thus it seems unlikely that failures of APDs from these positions will be a serious problem in CMS.

6.4 Comparison of different burn-in conditions

The results presented so far have not differentiated between the different burn-in conditions. For the 491 randomly selected APDs the first burn-in was always at 90 °C, with the APDs sometimes under bias and sometimes in foam, and the second burn-in was either at 80 °C under bias or at 90 °C in foam. There was no significant difference in the failure rate in either the first or the second screenings between these combinations. Table 5 gives a brief summary of the results, with 18 APDs from the five wafer positions with the known mask problems excluded. While the total failure rate varies between 0 and 10%, this is not significant considering the small sample size and large fluctuations observed from wafer to wafer in the mass production; further, the extreme failure rates are for APDs with the same conditions for the first burn-in. Nor was there any clear preponderance to pass the irradiation and then fail during the burn-in for any of the groups.

Burn in conditions	Number of APDs	Number failing S1 or S2
1st Bias 90 °C. 2nd Bias 80 °C	180	7
1st Bias 90 °C. 2nd Foam 90 °C	134	8
1st Foam 90 °C. 2nd Foam 90 °C	98	0
1st Foam 90 °C. 2nd Bias 80 °C	61	6

Table 5. Screening failures for groups of APDs with different burn-in conditions.

The 754 APDs selected for the double screening because they had failed the first screening were all burned in at 80 °C under bias both times, and the results for these cannot be meaningfully compared to those in Table 5.

7 The dark current development.

As has been mentioned earlier, the dark current induced by the first irradiation is typically reduced by a factor of about 6 by the first burn-in (but at values around 50 nA a factor 10-20 greater than before irradiation). But the dark current induced after the second irradiation is only about half that induced after the first irradiation. This may indicate that some surface defects are annealed away by the first burn-in. On the other hand, the dark current is not reduced as much by the second burn-in – indeed it typically ends up about one third higher after the second full screening than after the first screening. A plausible explanation would be that some damage which does not anneal away is induced by each irradiation, and this accumulates.

Figure 4 shows ratios of dark currents for all APDs passing both screenings, grouped according to the burn-in conditions. Some of the steps in the data (eg in the second and third groups) are due to Lot or wafer boundaries. This plot may indicate that the effect of the burn-in in foam is different to that of the burn-in under bias, since for these two groups the currents after the second burn-in are not lower than after the first; but in view of the large fluctuations in behaviour this cannot be considered a definite result.

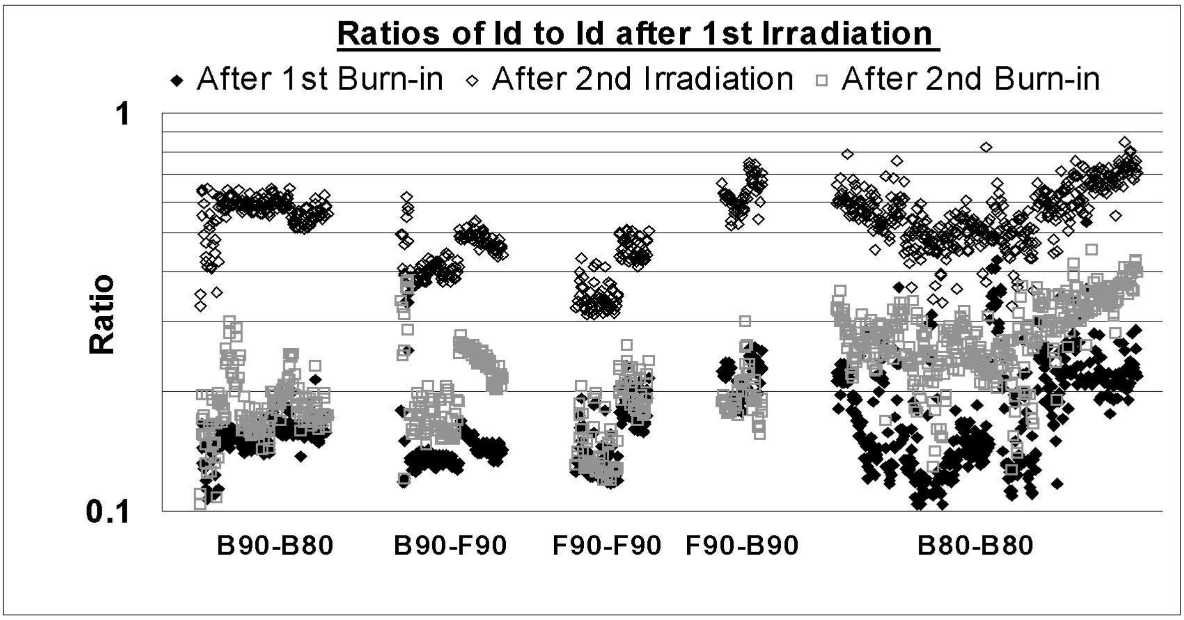

Figure 4. The ratio of dark current after the first burn-in, after the second irradiation and after the second burn-in, to that after the first irradiation. The data are grouped according to the burn-in conditions indicated below the horizontal axis, where B means under bias, F in foam and the number is the oven temperature (eg B90-F90 means first under bias at 90 °C, then second in foam at 90 °C).

8 Irradiations under bias

The standard screening of the APDs irradiates them mounted in conducting foam, but some tests were made with the irradiation being made under bias (followed by the standard burn-in). There appeared to be no difference in response for the two types of screening. However, some of the APDs used in this test were then included in the double irradiation tests, and all failed the second irradiation dramatically with Vb reduced by between 10 – 30 volts, but with normal values of Id at gain 50. After the standard burn-in the values of Vb recovered by some 13 V, so that in many cases the normal Vb was not restored. The behaviour was found to be clearly reproducible and insensitive to the intervening burn-in conditions. Further, APDs given a much lower dose, 0.36 kGy over 60 hours, showed a similar tendency if later given a standard 5 kGy irradiation.

Consequently some double screenings were carried out with both irradiations under bias, or with the first in foam and the second under bias, and with the burn-in between the two irradiations sometimes in foam at 90 °C, and sometimes under bias at either 90 °C or 80 °C. In none of these cases was there any unusual systematic change in Vb – only the original case of first irradiating under bias and then in foam caused the much reduced values of Vb (and, as said, this was shown to be reproducible).

These results are not understood and nor are we aware of a plausible explanation. They raise the question of whether they have implications for the reliability of the APDs in CMS. However, a small number of APDs which passed the standard screening and have been tested much later show no signs of instability.

9 Summary and relevance to CMS

The results for the main sample shown in Table 1 indicate a success rate for passing these double irradiation tests at the level of the desired 99.9% if the marginal failures in the second screening are ignored. Further, the one clear failure was not catastrophic. The rather small sample of APDs from Bad Positions shown in Table 3 also behaved reassuringly. But APDs from positions where inspection had indicated a fault in a production mask were very unreliable. The differing burn-in conditions, shared with a limited number of APDs to be installed in CMS, do not appear to have any effect on either the first or the second screening rejection rate.

The high first screening failure rate of APDs outside the final Hamamatsu specifications led to the agreement on these. Nevertheless, the double screening tests indicate that the small number of such APDs which passed the production screening and will be installed in the ECAL should be reliable.

One may thus conclude that the APDs installed in the CMS ECAL should be reliable at the required scale of 99.9%, and further, that there is no evidence in these tests of catastrophic failure of APDs which passed the first screening, even among the APDs from positions with mask faults. Hence any problem during the operation of ECAL seems much more likely to be noise generation than inoperability at the nominal bias voltage.

However, there are qualifications to these conclusions. In the main production of APDs for CMS, measurement of the noise after the irradiation was an important reason to reject APDs and these measurements were not available for the tests reported here. Further, there is no way of knowing a priori the relationship between the screening tests and operation for 10 years in the CMS environment. On the other hand, both the irradiation in 2 hours and the burn-in at 80 °C for four weeks are more violent treatments than that to be experienced in CMS, where the maximum annual irradiation will be at least an order of magnitude less than the screening dose, and where some self-annealing should occur.

Acknowledgements

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