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RADIATION DAMAGE IN PIN-PHOTODIODES

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The investigations of radiation damages to Si-PIN-photodiodes are done in view of their applicability as beam loss monitors for the HERA p-ring. The results indicate that photodiodes can withstand doses of 5×10^3 Gy without any problems, except a small increase of dark currents. Therefore, these diodes could be used as loss monitors in HERA for several years.

1. Introduction

The Hadron Electron Ring Accelerator HERA, presently under construction at DESY, consists of an electron ring of 30 GeV and a proton ring of 820 GeV nominal energies. Because of its high energy, the proton ring requires superconducting bending, focusing and correction magnets. In order to protect the magnets against beam induced quenches resulting from beam losses, a loss monitor system will be installed in the HERA tunnel. Experience from TEVATRON [1] shows that a loss of about 10^9 protons per millisecond inside one superconducting magnet could lead to a quench at 400 GeV. Calculations made by Otterpohl [2] predicted that of the order of 10^8 lost protons per millisecond will quench a HERA magnet at 820 GeV. If such a rate is reached, the beam loss monitor system has to initiate a beam dump before a quench occurs.

The main part of a planned loss monitor system, as proposed by Bailey [3], consists of photodiodes (PDs) which are located on top of a superconducting magnets, one PD on each magnet. The PD, used as a semiconductor counter, can detect the shower particles leaving the magnet which are generated by lost protons inside the magnet. The rate of shower particles crossing the PD is proportional to the loss rate *. The dose ** rate due to synchrotron radiation (SR) from the electron ring in the HERA tunnel is expected to be 2×10^2 Gy per year behind a few centimeter thick lead shield. The calculated spectrum of the SR ranges from 10^{-2} MeV up to about 1 MeV. The average is 0.1 MeV [5]. Thus, two problems arise:

- Background signals: their contribution is only 0.1% of the real signal rate used for system tests [4].
- Radiation damage: this effect will be discussed in the following.

* A detailed description of the planned beam loss monitor system will be available in the near future [4].

** In this report "dose" means a dose measured by a RPL glass dosimeter (see also ref. [6]).

2. Arrangement

The tested PDs were Si-PIN-photodiodes BPW 34 (Siemens) with a sensitive area of 0.075 cm^2 (fig. 1). The PDs were irradiated by a ^{137}Cs source (660 keV γ-rays) available from the DESY radiation safety group. The PDs were exposed to total doses ranging from 1 up to 5×10^3 Gy. The dose rates correspond to the total dose between 0.46 Gy/h at 1 Gy and about 10^2 Gy/h at 5×10^3 Gy. Three PDs were always irradiated simultaneously with the same dose to account for differences between the PDs. An RPL glass dosimeter was mounted near the irradiated PDs to measure the dose. During irradiation, a bias voltage of 9 V was applied to the PDs in order to represent the conditions in HERA.

The following measurements were made before and immediately after irradiation:

(1) dark current as a function of the bias voltage applied,
(2) noise determination with a sensitive preamplifier,
(3) 60 keV γ spectrum with the sensitive amplifier,
(4) noise determination with an amplifier which will be used for the beam loss system, and
(5) annealing effects.

Ad 1): The dark currents were measured with a nano-amperemeter – E.I.L. Vibron Electrometer model 33C. The uncertainty of this measurement is less than 10% as a result of reading errors.

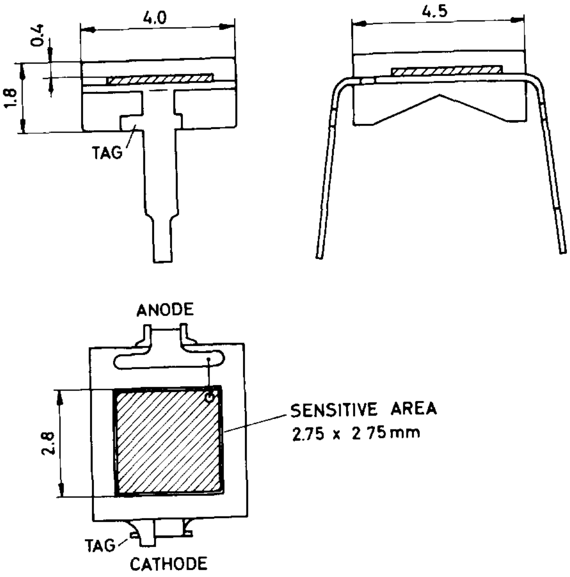

Fig. 1. Mechanical design of BPW-34 PIN photodiode.

Ad 2) and 3): To detect small changes of the PDs, a readout with a sensitive preamplifier–amplifier combination is necessary. A preamplifier – CANBERRA model 2003 BT, and a shaping amplifier – ORTEC model 451 (shaping time = 2 μs), were choosen. The pulseheight spectrum was analysed by a multichannel analyser – Tracor NORTHERN model TN-1705. To determine the noise, a well-defined test pulse was applied to the preamplifier. The width of the pulse height spectrum gives the noise of the whole readout system including the PD. The setup is shown in fig. 2. Furthermore, the spectrum of a ^{241}Am source, mainly the 60 keV γ-line, was measured with the PDs acting as semiconductor detectors.

Ad 4): To look at influences under real circumstances, the noise of the combination of a PD and an amplifier built for the use in HERA was monitored. For this purpose, the same measuring method as described in ref. [7] was used (see also fig. 3).

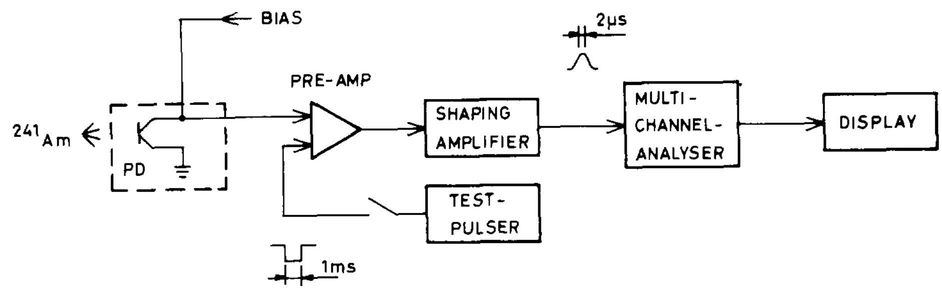

Fig. 2. Electronic setup with the sensitive amplifier configuration.

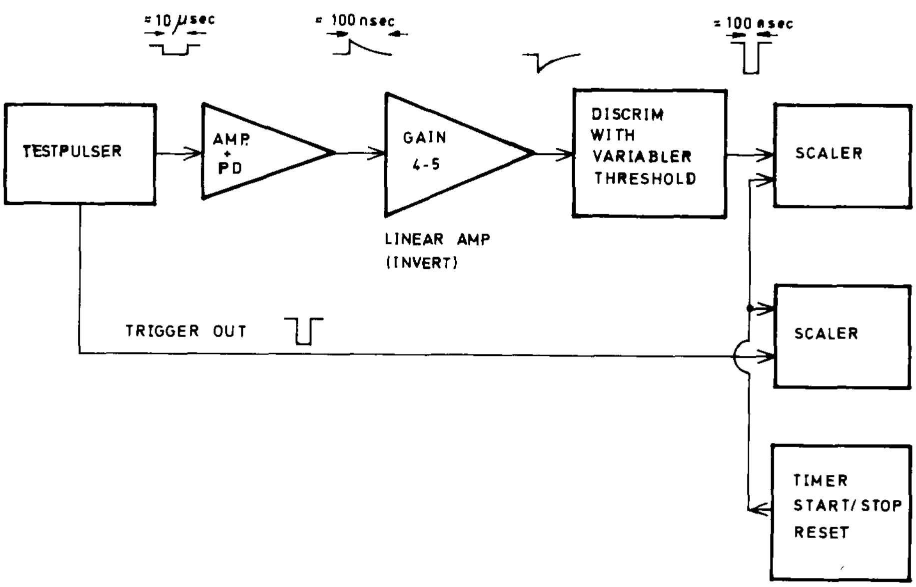

Fig. 3. Electronic setup with the HERA amplifier.

Ad 5): To monitor the annealing effect of irradiated semiconductor devices, the dark currents of the highly irradiated sample of PDs (5×10^3 Gy) were monitored for up to 16 days after the end of irradiation.

For all these measurements, non-irradiated PDs were used to control the stability of the readout electronics. During the measurement period, temperatures varied by up to $\pm 2°$ C. No influence as a result of this variation was detected.

3. Results

In all cases, the PDs of the same irradiated sample show the same behaviour, so the diagrams show the results for one of them only.

3.1. Dark currents

Increases in dark current are observed at doses of more than 10^2 Gy (figs. 4–6). At 5×10^3 Gy all three irradiated PDs show an increase by a factor of 5–10 at bias voltages below 10 V and by a factor 2–3 at bias voltages above 10 V. The annealing of the PDs is shown in fig. 7. After 16 days the dark current decreases to one half the value measured immediately after irradiation.

3.2. Noise

The increases in dark current cause increases in (shot-) noise. This is detectable with the sensitive amplifier configuration (fig. 8). But no significant change in noise was detected with the amplifier for HERA (fig. 9). This result indicates that this amplifier produces most of the noise (transistor noise) and the PD contributes only a little.

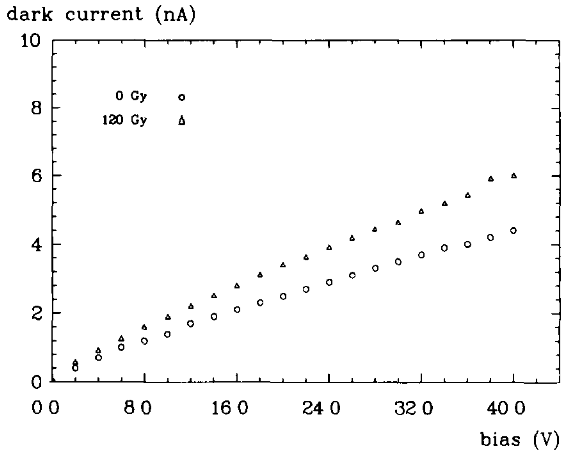

Fig. 5. Dark current versus bias (sample 2).

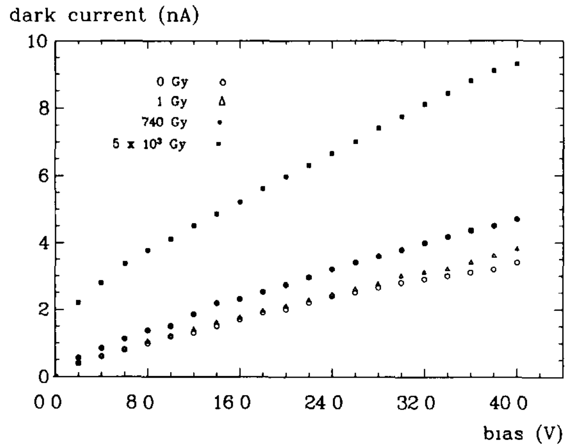

Fig. 6. Dark current versus bias (sample 3).

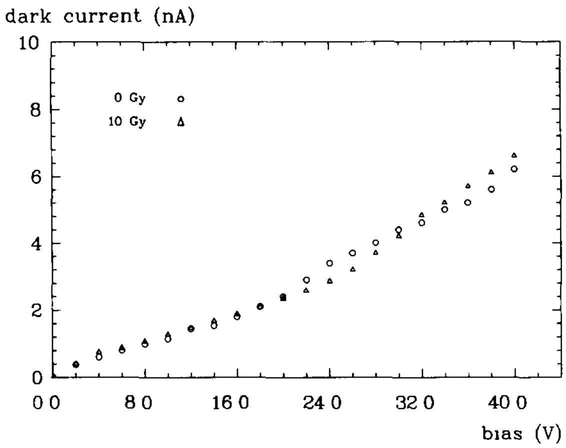

Fig. 4. Dark current versus bias (sample 1).

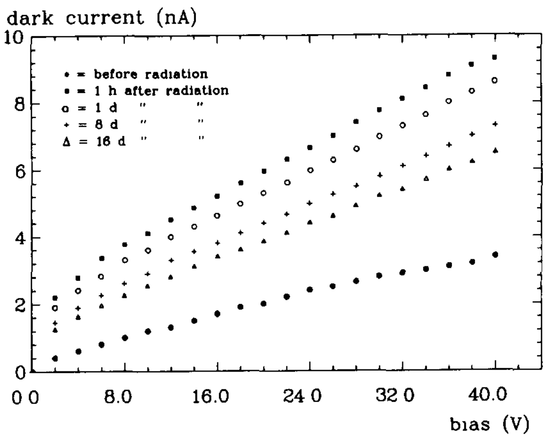

Fig. 7. Annealing after exposure to 5×10^3 Gy (sample 3).

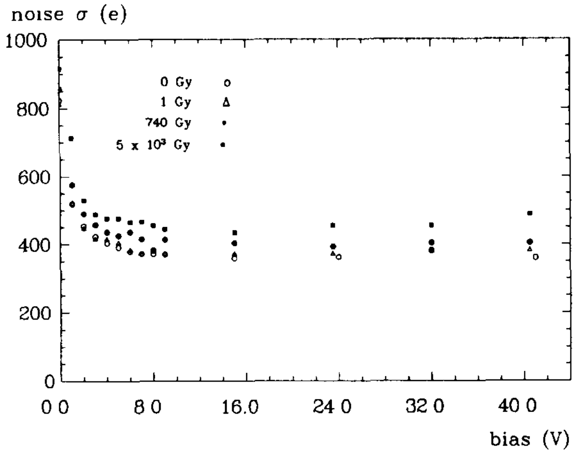

Fig. 8. Noise measured from the sensitive amplifier configuration.

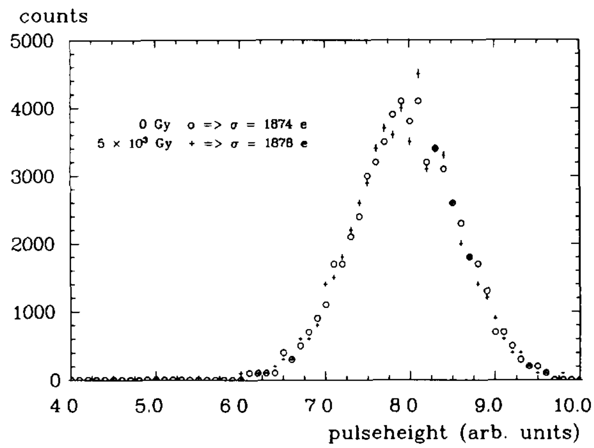

Fig. 9. Noise measured by the HERA amplifier.

3.3. 60 keV spectrum

Table 1 shows the calculated values of the 60 keV peak in units of the electron–hole pairs produced. The values can be calculated with the test pulse calibration method [8]. The relative uncertainty of the values is less than ±1% as a result of reading errors. The absolute uncertainty is ±200 electron–hole pairs because of an inexactly adjustable test pulse amplitude and an inaccurate input capacitance. Within these errors here is no change observable. The small decrease at 5×10^3 Gy which also occurs at the control PD (check), is likely to be due to a small shift of the test pulse amplitude. In conclusion, no remarkable change of the PD properties of charge creation and charge conduction has occurred.

Table 1
Mean number of electron–hole pairs created by a 60 keV photon

PD no.	Before irrad.	1 Gy	7.4×10^2 Gy	5.0×10^3 Gy
1	16884	16834	16910	16767
2	16900	16834	16834	16750
3	16850	16800	16733	16741
check	16876	16876	16902	16741

3.4. Check

No changes are found in any of the control values during the measurement period indicating that the readout electronics were stable.

3.5. Comment

The results indicate that the PDs have sufficient resistance against synchrotron radiation. Without any problems they tolerate more than the γ-ray dose of 2×10^2 Gy per year expected in HERA. They can be used as beam loss monitors in the HERA tunnel for several years.

4. Calculations and discussion

The main radiation effects in a silicon lattice are displacements of Si atoms from their lattice site (knock-on atoms) [9,10]. Photons can displace atoms directly by photonuclear absorption, but the cross section for this effect is small compared to the cross section for Compton scattering in the energy range of the synchrotron radiation in HERA. An electron produced by the Compton effect undergoes a collision with a lattice atom and transfers sufficient kinetic energy to knock it out of a lattice site. In most materials, the atom has to receive an energy of more than ≈ 25 eV for dislocation to occur [10–12]. The energy transfer T (from an incident electron with an energy of E ($mc^2 = 511$ keV) to an Si atom ($Mc^2 = 28$ GeV) can be obtained as:

$$T = \frac{2E(E + 2mc^2)}{Mc^2}.$$

The energy E of an electron after the Compton scattering of photons of an energy $h\nu$ is:

$$E = mc^2 \times \frac{\epsilon^2(1 - \cos\Theta)}{1 + \epsilon(1 - \cos\Theta)},$$

$\epsilon = h\nu/mc^2$,

Θ = scattering angle.

With $h\nu = 660$ keV it follows that photons with a scattering angle of $\Theta \gtrsim \pi/3$ yield electrons of sufficient energy to produce displacements. The calculated cross

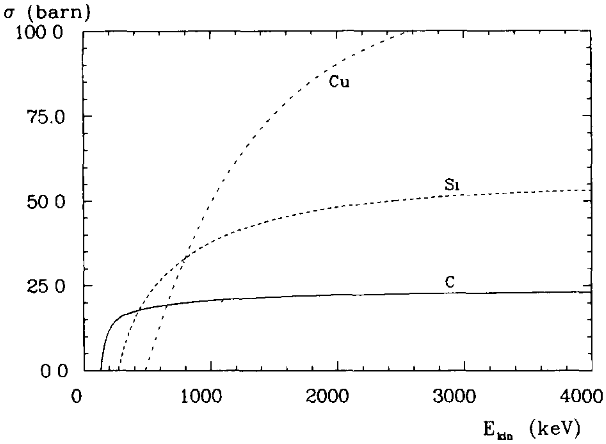

Fig. 10. Cross section for knock-on atoms by incident electrons.

Table 3
Probability P of defects as a result of incident particles

Particle	Energy (MeV)	P/100 μm Si	Ref.
Electron	0.2	8×10^{-3}	[15]
	2	5×10^{-2}	[12]
	40	1.9×10^{-1}	[15]
Proton	2	20–40	[9,12]
	10	10	[9,15–17]
	100	1–3	[9,15–17]
	500	0.3	[15–17]
Neutron	1	5	[15]
	2	2.3	[12]
	14	35	[15]
Photon	0.66	3×10^{-6}	this report [14]

section σ_c for the Compton scattering of 660 keV photons within this angular range is:

$\sigma_c = 0.66$ b.

The probability P_c for a Compton effect with $\Theta \geq \pi/3$ to take place inside a 100 μm Si layer 1 (= intrinsic layer of the tested PDs) is:

$P_c = \sigma \times 1 \times n, \qquad n = 5 \times 10^{22}$ at/cm^3.

resulting in: $P_c = 3.3 \times 10^{-4}$.

The cross section for displacements due to electron bombardment was calculated by ref. [13] (see also ref. [10]). Fig. 10 shows the result. From this diagram it is possible to estimate the cross section $\sigma_{\text{knock on}}$ for low energy electrons:

$\sigma_{\text{knock on}} \approx 20 \text{ b} \rightarrow P_{\text{knock on}} \approx 10^{-2}$.

Then, the probability of a defect inside a PD (100 μm Si-layer) is:

$P_{\text{defect}}(\gamma) = P_c \times P_{\text{knock on}} \approx 3.3 \times 10^{-6}$.

This result complies well with other authors [14].

Table 2 lists the number of 660 keV photons N which have crossed a PD at a certain dose. This number can be calculated on the basis of the mass energy absorption coefficient of the RPL glass dosimeter at 660 keV ($\mu/\rho \approx 3 \times 10^{-2}$; [18]). Together with the probability for a defect as calculated above one can estimate the number of defects M inside the PD as a function of the measured dose D. Note that M means the number of defects created by the 660 keV radiation without annealing. Ref. [9] deals with an annealing factor of 50%, also measured in this report. This annealing allows the PD to tolerate higher accumulated doses of radiation as defects are self healing at a rate near that at which they are being created.

Table 2
Number of defects created by radiation

D (Gy)	N	Defects M
1	2.4×10^{10}	8×10^{4}
10	2.4×10^{11}	8×10^{5}
1.2×10^{2}	2.9×10^{12}	9.7×10^{6}
7.4×10^{2}	1.8×10^{13}	6×10^{7}
5×10^{3}	1.2×10^{14}	4×10^{8}

The PDs used as beam loss monitors in HERA will not be exposed to synchrotron radiation only. The aim of such a monitor is to measure particles from hadronic showers. Table 3 gives an estimate of the probability of defects created by incident shower particles. The comparison of different particles has to be done carefully because the values given are often mean values, and the types of defects are different. The defects resulting from electron and photon bombardment are homogeneously distributed over the whole crystal. Protons stop at the end of their range so that defects are clustered at this point. Hence, protons with an energy above 10 MeV will hardly lead to defects inside a 100 μm Si layer. The radiation level caused by shower particles will depend on the frequency of beam losses in the same magnet in HERA. Monte Carlo calculations show that of the order of 10^4 shower particles would cross the PD if 10^8 protons hit the magnet [4]. Most of these particles are electrons and positrons. The probability for a defect from an electron is about 0.1. This leads to 10^3 defects per quench in a 100 μm Si layer. To produce more than 4×10^8 defects, more than 4×10^5 beam induced quenches inside the corresponding magnet would be necessary. This number is unlikely ever to be reached in the whole life of HERA. The fraction of hadronic particles is about 10^{-2} lower than the electromagnetic part. So there will be no danger from the hadrons, either.

Table 4
Allowable fluences through a 2 mm lithium drifted Si-layer

Particle	Energy (MeV)	Fluence/cm^2
Electron	0.6	10^{15}
	1.5	10^{13}
Proton	1.9	10^{11}
Neutron	fast	10^{10}

The situation is a little bit different for small continuous beam losses: assuming that HERA operates 4000 h/yr. For 10^8 defects inside a PD one needs 10^3 protons per millisecond lost inside the corresponding magnet, continuously, 4000 h/yr. If this happens in all superconducting magnets it will lead to a beam lifetime of about one order of magnitude lower than the design value. Such a loss rate is not tolerable for HERA. If only a few magnets are affected then the total loss rate is smaller, the loss rate inside a magnet may be larger and more than 10^8 defects per year are possible for the corresponding PD. But note three points:

(1) The PDs will work very well with 10^8 defects.

(2) With data from the literature one can expect much more tolerable doses for the PDs. Ref. [19] had listed the following "allowable" fluences of particles through a 2 mm thick depletion layer of a lithium drift Si-crystal (see table 4). It is remarkable that the "allowable" fluence multiplied with the probability for a defect listed in table 3 give results which are of the same order of magnitude for all particles ($\approx 10^{14}$ defects/cm^3). This indicates that the number of defects in a Si layer are nearly independent of the incident particles and their energies. In the case of the tested PDs this number is about 10^{11} defects. Surely, this value is a rough estimation, but shows that one is on the safe side in case of the beam loss monitor.

(3) PDs are inexpensive and will be easy to exchange when working as beam loss monitors of the HERA tunnel.

5. Summary and conclusions

γ-doses of up to 5×10^3 Gy lead to a small increase in dark current in PIN photodiodes. This does not affect their operation as beam loss monitors for the HERA p-ring. They are not affected by beam loss radiation beyond very tolerable levels. In view of another application in high energy physics these results indicate a favourable use of PDs also in the readout of scintillation counters. In a radiation environment there will be no problems with radiation damage of the PDs. The main problems are the damage of the scintillation material (see e.g. ref. [20]).

For the readout of the PDs one needs an amplifier mounted close to the PD. This amplifier is exposed to the same radiation level as the PD. Therefore it is necessary to test the behaviour of the HERA amplifier at a certain radiation dose which we are planning.

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