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Proximity focussed Hybrid Photo Diode characteristics evaluations

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ABSTRACT

The Hybrid PhotoDiode (HPD) tube is a new kind of photodetector. Characteristics of proximity focussed HPD tube prototypes are reported. Insensitivity to magnetic fields to the Tesla level, fast response (few ns rise and fall time), good response uniformity and linearity over 8 orders of magnitude were measured. Particular attention was paid to voltage and charge response to high intensity light pulses. The HPD prototypes reported here are the precursors of a family of multipixel HPDs foreseen for the second half of 1993.

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1. INTRODUCTION.

Two different tube designs of proximity focussed, single pixel HPDs have been developed and built at DEP; their tests are reported in this paper. The HPD tubes here discussed are an intermediate step in a long term, comprehensive tube development project¹⁻² made in collaboration with Canberra, DEP, INFN and the CERN-LAA project. This development sparked a widespread interest in the HPD light detector concept, both in the industrial and the scientific community³⁻⁴⁻⁵. Tests on earlier versions of proximity focussed tubes, also provided by DEP, have been reported in ref. 5.

The HPD idea dates back to the fifties⁶, the HPD development was started in different occasions but always abandoned because of technical difficulties. The HPD tube is conceptually very simple, being constructed by mounting a planar silicon diode in a vacuum tube facing a PhotoCathode (PC). The photoelectrons (p.e.s), accelerated typically by a 10 kV potential drop, bombard the silicon diode generating an electrical signal in the form of electron-hole pairs in the bulk of the reversely biased diode.

The main advantages of the HPD over PhotoMultiplier (PM) tubes are derived from its simplicity; the recognition of these advantages⁷ (listed below) generated a revival of the HPD R&D efforts.

The entire dynode structure disappears, replaced by a simple focussing electrode in the case of electrostatically focussed versions¹⁻² or by a vacuum gap in the proximity focussed types discussed in this paper (figure 1).

The HPD is a purely electrostatic device with no idle power consumption; for this reason, although it works at higher voltage than PM tubes, it is possible to locally power it and to procure it with built-in, low consumption power supplies. Due to its rotational symmetry and favourable geometry, the HPD p.e. collection is practically 100% effective and uniform.

Proximity focussed geometry allows HPD operation in strong magnetic fields.

Signal generation is obtained in a single, dissipative step as the p.e.s are received and stopped in the silicon. The resulting electrical signal amplitude for single electrons has a gaussian distribution without signal tails which is particularly suitable for photon counting and very low light level thresholds.

Well defined single p.e. response signals, combined with stiff p.e. trajectories, are ideal for precision photon timing. Moreover, the suppression of the dynode structure eliminates the often disturbing pre-pulsing and after-pulsing effects seen in fast PMs.

The single-step gain process insures that the gain is a linear function of the applied high voltage bringing, as a consequence, obvious advantages in signal stability². Since the silicon diodes are very resilient to saturation, the HPD has proven to be linear over many orders of magnitude of signal amplitude, even with very fast pulses.

Finally, the HPD can be pixelized by simply printing pixels on the anode planar silicon diode.

This paper will describe the detector, the instrumental setup and measurements of gain, speed, linearity, saturation, response uniformity, magnetic field behavior, single p.e. response and lifetime.

2. DETECTOR AND MEASUREMENT SETUP DESCRIPTION.

The HPD tubes have been built at DEP. Two models of proximity focussed tubes were extensively tested. The first model (T1), shown in figure 1, is an intermediate prototype intended mainly to test PC and silicon compatibility in a proximity focussed geometry. The silicon diode was a 8 mm useful diameter, 300 micron thick Particle Implanted Passivated Silicon (PIPS) diode made by Canberra in the "E" type configuration with full depletion at 20 volts. The nominal gap between the PC and the silicon chip was 1.8 millimeters. The second tube tested (T2) was a more advanced and more compact tube, built without magnetic materials behind the silicon chip for magnetic field studies; this second tube also had an "E" type silicon chip of 11.7 mm useful diameter, 300 micron thickness and full depletion at 50 volts. The nominal gap between the PC and the silicon chip was 1.6 millimeters.

Both tubes had a 6 μ m fiber optical window carrying an S20 photocathode much larger than the silicon chip diameter. The PC spectral response is shown in figure 2.

The two tubes generally behaved in a similar way; no significant differences were noted except during magnetic field operation.

Most of the measurements reported were performed using the data acquisition system described in figure 3.

For large signal operation the signal went directly either to a 9450 LeCroy or to a Tektronix SCD 1000 transient digitizer.

For small signal operation, a simple charge amplifier⁸ was mounted next to the HPD.

For time resolved measurements the LED was replaced by a 300 ps pulse-length dye laser at 500 nm wavelength. The laser light pulse was transported in a multimode optical fibre.

Two additional proximity focussed tubes were dedicated to PC ageing studies performed at DEP.

3. GAIN, SPEED AND LINEARITY MEASUREMENTS.

The HPD gain measurement was performed using a pulsed LED light source. The gain normalization was obtained by short circuiting the two ends of the silicon chip and using it as a simple collection electrode for p.e.s. The gain as a function of voltage is shown in figure 4. At low PC bias, both positive and negative, an "apparent gain" of 2 was observed even with no p.e.s reaching the silicon. This "apparent gain" is due to the fact that the PC is semi-transparent with 30-50% transmission; the transmitted light is then detected by the silicon target that, having the structure of a PIN diode, acts as a normal light detecting diode.

At normal (negative) PC voltage, the HPD behaves as expected; the gain threshold was found at 2.1 kV of PC polarization, corresponding to a 0.135 (+/-0.005) micron contact layer on the bombarded surface of the silicon chip⁹. At low PC polarization voltage all p.e.s stop in this heavily doped conductive layer, the electron-hole pairs quickly recombine and no signal is produced.

As the PC voltage is increased, the p.e.s start reaching the active volume in the chip and generate a signal. Several factors play a role in determining the gain threshold voltage. The heavily doped contact layer is obtained by implantation and its border with the intrinsic-silicon depleted volume is somewhat blurred by the exponentially falling implanted ion distribution. The electron/holes released in this transition region have a short recombination lifetime and will be only partially collected. The implanted layer thickness may vary a little across the chip surface. The p.e. range fluctuations induce large fluctuations of the number of electron/hole pairs released in the active volume (this last effect is expected to dominate all the others). As a net effect the start-off of the gain curve is smoothed out.

When a sufficiently high voltage is applied to the PC, a p.e. can pierce clearly through the contact layer into the fully depleted bulk of

the silicon diode; there the electron-hole pairs are efficiently swept out and collected by the electric field of the bias voltage applied to the diode. Above the threshold, higher PC voltages simply induce more available energy to free more electron-hole pairs for the signal. The slope of 0.35 (± 0.05 systematic error) electron-hole pairs per electron-volt above the knee is in reasonable but not complete agreement with the commonly accepted silicon ionizability from minimum ionizing particles (0.276 electron/hole pair per electron-volt).

Signal speed and linearity were measured with the help of laser light pulses attenuated with combinations of calibrated optical filters. A 200 meter long light fiber was used to carry the light from the laser to the HPD. The delay introduced by the fiber allowed one to perform the signal measurements well after the electromagnetic laser noise had died off. The fiber also introduced a light pulse spread resulting in a 1.6 ns rise time. The illumination was uniform across a spot of 6.5 mm diameter. The HPD was operated at 7 kV of negative PC voltage and 95 V diode bias. A Phillips 6931, 100 MHz, 100x amplifier or passive attenuators were used to fit the signal into the Tektronix transient digitizer dynamic range. The light pulse amplitude was tuned with combinations of calibrated neutral density filters. Signal integrated charge, pulse amplitude, rise, fall and FWHM times were recorded. A typical signal, for the T1 HPD is shown in figure 5; due to the large chip area (50 mm²) and surface resistivity, the rise and fall times are much larger than the 1.6 to 1.7 ns measured in smaller diode HPDs (ref. 2).

The linearity measurement results are shown in figures 6 and 7. The HPD pulse height response (figure 6 lower, right distribution) saturates above 5 Volts signal (over 50 Ohms), corresponding to 4×10^6 p.e.s in the previously described working conditions. The HPD charge response (figure 6 top and left distributions) proved to be linear up to more than 10^4 pC corresponding to almost 10^8 p.e.s per pulse. The charge linearity tests were not carried out further because of transient digitizer integration window limits. The measurements in the first 2 orders of magnitude were performed with the help of the charge amplifier and present a somewhat different normalization.

4. SATURATION STUDIES.

Coherently with figure 6, the rise and fall times of the signal, shown in figure 7, remain constant up to a few millions p.e.s where the pulse height saturation begins. Notably, the signal shape saturation occurs above a delivered charge of 2000 pC, practically corresponding to the point when the entire stored charge (in the 29 pF chip capacity under the 95 Volts bias) is used up. The remaining signal must be fed in by the bias circuit. The signal rise time is almost constant at all light pulse amplitudes; the increasingly longer fall times have to be considered as a characteristic of the bias circuit design.

With fast, tightly focussed, very high intensity light pulses and high HPD gain, it is possible to generate electric signals with charge amplitude much higher than the charge stored in the light spot neighborhood in the silicon chip. While they separate, the electrons and holes of the signal charge cloud perturb and locally overwhelm the bias electric field, strengthening it in front and reducing it behind their path.

This effect was tested by focussing the laser light pulses over a diameter of 0.1 millimeters and generated a family of signal curves, four of which are shown in figure 8. The relative amplitudes of the light pulses used are 1, 10, 100 and 1000 for the four curves; the smaller light pulse corresponds to $1000 \div 1500$ p.e.s. At the beginning, only a fast pulse is visible (8 A), it gradually widens (8 B); then a flat tail appears behind the initial pulse as the signal charge cloud begins to overwhelm the bias field (8 C). The tail extends more and more in time as the light amplitude is increased (8 D). The fast pulse at the beginning of the signal is probably due to the collection of the electrons generated deepest in the silicon that are not delayed by the space charge. The tail is due to the slow separation of the rest of the signal plasma cloud under the residual field in the silicon. This effect is local (the light spot dimensions, being three times smaller than the chip thickness, can be considered point like) and stay limited to a portion of the chip; in fact only 720 pC, out of the 2700 pC available from the rest of the chip, were delivered by the biggest pulses. The charge integrated under the prompt signal peak is histogrammed versus light pulse amplitude in figure 9 (circles). Because of the bias field saturation, the response is not linear and rather follows a power 0.75 law.

If the total delivered charge (including tails) is histogrammed instead (figure 9, black diamonds) all but the last two measurement points stay on a unitary slope, indicating the almost complete absence of electron-hole plasma recombination. It must also be noted that a maximum pulse of 300 fC was extracted from a 100 micron diameter section of the PC, which may well be the culprit for the charge saturation in the last two points.

Extensive tests were performed with different silicon diode bias voltages. Higher bias voltages were found to decrease the HPD response time, especially at high pulse amplitudes. In figure 10 the rise, fall and FWHM times of the HPD are shown as a function of the bias voltage. As in the case of the saturation, the rise time is practically unaffected by the bias voltage.

Further tests varying, independently, the light pulse amplitude and duration, the HPD gain and the silicon diode bias voltage confirmed that the observed saturation is purely a charge effect inside the silicon chip. These tests proved that, as with simple modelling, the saturation levels are trivially governed by the bias voltage, the total amount of charge injected in the silicon, the spatial distribution across the chip of the injected charge and the duration of the light pulse. Virtually no charge recombination was ever measured above the silicon diode full depletion voltage.

5. UNIFORMITY MEASUREMENT.

The sheer simplicity of the HPD is expected to generate a good response uniformity across the detector. The response uniformity is particularly necessary in precision calorimetry where, ideally, elements of a calorimeter should all be read out with uniform efficiency.

The uniformity measurement was performed with the help of a small optical fiber that could be micrometrically positioned anywhere over the input window. The HPDs' windows, made of 6 micron diameter glass fibers, fully preserve the light spot geometry. The light fed in the test fibre was generated by a LED diode. The HPDs were scanned in a matrix fashion.

A central slice of the measurements is shown in figure 11. The HPD signal is flat across the diameter. Also, some residual signal is observable after the light spot has left the chip edge. This effect can be

explained if the following arguments are taken into account. The semitransparent PC has been excited with a small light spot, but with large divergence. The silicon chip target is polished and partially reflective on the sensitive area, aluminized and well reflective elsewhere. The light hitting the PC is partially transmitted, then reflected on the chip surface and deposited back on the PC within a circle of dimensions comparable to the distance between the PC and the chip. As the light pencil is well inside the active region of the silicon chip this effect produces a small apparent enhancement of the PC efficiency.

When the light pencil leaves the silicon chip active area, a considerable fraction of the transmitted light is reflected by the aluminized chip edge (and by the chip holder) back towards the photocathode over the chip active surface. This reflected light generates the observed residual signal.

Superimposed with this effect is the halo produced by the electron back-scattering at the silicon surface. These back-scattered electrons would be pushed back onto the silicon chip, also in a circular pattern, by the accelerating electric field.

Both effects produce a halo which is a peculiarity of proximity focussed tubes and can generate a cross-talk problem in a multipixel HPD version. The back scattered electrons are naturally constrained in the presence of a magnetic field; the reflected light halo can be depressed if the silicon surface is kept dark. An important consideration is that the reflected light effect can be exploited by purposely aluminizing the silicon surface if a boosted PC efficiency is required at the expenses of pixel cross-talk. From the detector user point of view, it has to be noted that the dimensions of the halo depend linearly on the distance between the PC and the silicon chip and on the divergence of the light deposited on the PC.

A fine scan of the silicon chip edge (figure 12) and its derivative show a convoluted light spot and HPD edge resolution of 40 microns, in good agreement with the expected resolution of the 100 micron diameter optical fiber used in the scan. This measurement, modulo the previously discussed halo, gives an upper limit of the pixel sharpness in future multipixel HPDs.

Tests of temporal response uniformity were performed in the same setup. The LED was replaced by the fast laser. The laser output was attenuated to obtain roughly 100 mV pulses from the HPD in order to

avoid trivial saturation and/or slew effects. The laser pulses delivered 50% shot-to-shot amplitude variations. Both the laser pulse (readout by a fast silicon diode) and the HPD signal were discriminated on a Phillips 715 Constant Fraction Discriminator (CFD) and used as start and stop signals on a Silena Varro 8K Multi Channel Analyzer. Each measurement corresponds to at least 500 laser shots. The result of two position scans across the HPD surface is shown in figures 13a and b for the HPDs T1 and T2 respectively.

Both HPDs show delayed response from the center of the silicon chip as expected if the well known iris delay effect¹⁰ is applied to the silicon chip surface. Since the iris delay is quadratic with the diameter, the larger diameter diode should, and does, show a time delay twice as long as the smaller one. The measurements are also in agreement with previous PIPS diode data¹¹. Just as performed in reference 11, in future tubes the iris timing variations can be eliminated by increasing the surface conductivity with lines, or even a thin aluminum layer, deposited over the chip.

6. MAGNETIC FIELD TESTS.

Careful measurements of the HPD performances have been done with magnetic field at 0°, 30°, 41.5° and 90° with respect to the accelerating electric field. In most tests the magnetic field was technically limited to 4 KGauss. The pole-tip gap dimensions did not allow HPD tilting between 41.5° and 80°. Two additional and quick tests at 0° and 30° were performed up to 20 kGauss using a different magnet. The high field magnet was available only for a very short time and the experimental setup could not be made very stable. In particular, the pulsed LED, used as light source, was rudimentally positioned onto the HPD surface, and the magnetic field, acting on the nickel plated LED legs, could have displaced it. In order to avoid trivial image shifting effects, the HPD was excited with the light source shining only in the center of the PC. Since the LED was placed inside the magnetic field its insensitivity to the field was checked by connecting it to an external PM via an optical fibre. In order to limit systematic errors all measurements were performed both while ramping up and ramping down the magnets.

The magnetic field test results are shown in figures 14 (magnetic field at 0°), 15 (at 30°), 16 (at 41.5°), 17 (at 90°).

No response variation is expected if the magnetic and electric fields are parallel. Overall, the results of figure 14 are in good agreement with theory. The 6% amplitude variations and hysteresis as the magnetic field is changed are attributed to the LED movements. The lower points are obtained systematically while ramping down the magnet.

When the magnetic field forms an angle with the electric field the p.e.s are accelerated along a spiral which loops around the magnetic field lines (see the appendix for details of calculation). The p.e.s still reach the silicon surface with full energy, although in a displaced position and with variable impinging angle. No signal cutoff is expected in this configuration unless the p.e.s are dragged outside of the chip active surface. Since the light spot was small and centered on the silicon chip, little effect is expected from the apparent spot displacement. Conversely, as the bombardment angle increases the dead contact layer on the silicon chip becomes increasingly difficult to penetrate and the signal is expected to decrease with increasing magnetic field. The measurements, figures 15 a (field at 30°) and 16 (field at 41.5°), are, at low field, in very good agreement with this mechanism, including the progressive loss of signal as the magnetic field is increased and the signal minima corresponding to the fields at which p.e.s make half a spiral loop before they encounter the silicon diode surface. The results, shown in figure 15 a, deviate at high field from the predicted behaviour because of the same technical limitations (LED movements) of the 20 kGauss axial field scan. The predicted behavior for 60° is shown in figures 15 b; it is interesting to note how the strong response dip at low field washes out at higher field strengths.

If the magnetic field is perpendicular to the electric field, the p.e.s follow a cycloid curve. If the cycloid height is larger than the distance between the PC and the silicon diode a signal is expected while no signal can be generated if the magnetic field is strong enough to deflect the p.e.s before they reach the chip.

As the magnetic field approaches the cutoff value, the p.e.s hit the silicon at smaller and smaller angles (with the silicon surface) experiencing increasingly larger losses in the dead contact layer.

As expected, in figure 17 the signal decreases as the bombarding electrons are slanted by the magnetic field and then abruptly falls when the magnetic field becomes sufficient to turn the p.e.s back toward the

PC. The cutoff value of the magnetic field corresponds to a cycloid height $h = k E/H^2 = 1.60 \text{ mm} \pm 0.02 \text{ mm}$, in complete agreement with the 1.6 mm nominal PC to chip separation.

The solid curve shown in figure 17 is a simulation obtained by assuming that the p.e. losses are simply proportional to the dead layer thickness divided by the cosine of the incident angle. Despite the oversimplified assumptions, the curve fits very well the data. The small discrepancy near the cutoff value is accounted for if the multiple scattering random walk of the electrons is considered.

The residual signal above the cutoff value was explained as follows. Above the cutoff value, the p.e.s follow a cycloid that carries them away from the light spot along the PC plane. The p.e.s that are not re-absorbed by the PC at the spikes of the cycloid, travel side-ways and eventually collide on the 0.4 mm thick walls of the chip positioning ring with an energy comparable to the PC potential. The subsequent soft X and hard visible fluorescence is then detected by the silicon diode. As the magnetic field is increased to 2 KGauss, the cycloid becomes small enough so that the p.e.s miss the ring and the residual signal disappears(*). In any case, the observed effect is of no consequence in typical HPD operation.

The T1 tube (and the similar design devices tested in ref. 5) behaved in a more unpredictable way than in figure 17 because of magnetic components in the tube funnelling and distorting the magnetic field. Indeed, so much magnetic material was present in the T1 tube that it broke down during the magnetic field tests. The breakage resulted to be a displacement of the chip and could be repaired, once, by banging the tube on the table.

(*) It would be expected that all the p.e.s, bent back by the magnetic field, would be re-absorbed by the PC at the first cycle, however, just above the cutoff magnetic field value, the p.e.s skim the silicon surface, there generating an image charge. Due to surface resistivity, this image charge drags the p.e.s, reducing their energy and dampening the cycloid, thus impeding the p.e.s return to and recapture from the PC. At higher magnetic fields the electrons pass farther away from the silicon surface, losing less energy, and can be re-absorbed by the PC.

In order to better understand the behavior of the HPD in transverse magnetic fields, measurements at constant chip bombardment angle were performed. To keep equal p.e. trajectories (and hence equal chip bombardment angle) the accelerating voltage and the transverse magnetic field were varied together in order to keep a constant scale factor $\alpha = V/B^2$ (where V is the PC voltage and B is the crossed magnetic field strength). One of the resulting plots is shown in figure 18. This curve, as expected, shows an increase of the gain threshold value and a smoother transition to the linear gain region.

7. SINGLE ELECTRON RESPONSE.

The Single Electron Response (SER) of the HPD can be quite good²; Some SER tests were performed also on the proximity focussed tube T1. The measurements were performed with the charge amplifier (characterized in ref.6). The signal was digitized on the Silena MCA. The light was produced by a LED driven by a programmable pulser. The test was performed at the maximum prototype tube voltage of 9 kV. The low light pulse intensity was obtained by setting the LED driver pulse length to 10 ns and by progressively reducing its pulse amplitude.

The response spectra for two low light amplitude levels is shown in figure 19.

Despite all efforts, pulsing the LED always injected some signal and some noise in the charge amplifier; as a result the position and width of the pedestal peak changed slightly if the LED was switched off. For this reason, the position and width of the pedestal were evaluated by fitting the pedestal shape of the 0.26 p.e. spectrum. The pedestal was subsequently eliminated by subtracting the two p.e. spectra as shown in figure 20. The PHA horizontal scale was also shifted until the origin coincided with the pedestal peak center. Subsequently, the subtracted and shifted spectrum was fit with the function:

$$y = A_1 e^{-\frac{(g-x)^2}{\sigma_{ped}^2 + \sigma_{SER}^2}} + A_2 e^{-\frac{(2g-x)^2}{\sigma_{ped}^2 + 2\sigma_{SER}^2}} + A_3 e^{-\frac{(3g-x)^2}{\sigma_{ped}^2 + 3\sigma_{SER}^2}} + \dots$$

where

g is the HPD gain in PHA channels,

σ_{ped} is the pedestal width fit on figure 19,

σ_{SER} is the Single Electron Response width and

$A_1, A_2, \dots$ are normalization coefficients.

The resulting fit gives the solid line in figure 20.

Using the gain curve of figure 4, the spectrum scale could be calibrated in absolute gain. From the fit a $\sigma_{\text{ped}} = 1350$ electrons per pulse and a $\sigma_{\text{SER}} = 430$ electrons were obtained for a gain of 2400. The higher than expected σ_{ped} was probably due to electronics-injected noise, to the silicon diode leakage current, to ambient light leaking on the PC and from the PC dark current noise. The single, double and multiple p.e. peaks could not be properly separated because of high voltage limitations peculiar to the construction of this first prototype. Further proximity focussed HPD tubes are thus expected to show well separated p.e. peaks just as observed in previously tested cross focussed HPD models.

Statistically, at a gain of 2400 a width $\sigma_{\text{SER}} = \sqrt{2400} = 50$ electrons would be expected. A factor ten higher σ_{SER} was observed instead. The cause of this worse than expected behavior is to be found with p.e. range fluctuations, the same reason that generates signal in figure 4, even at PC voltages below threshold. In order to have a stable and narrow SER spectrum, the p.e.s must be accelerated much beyond the gain threshold voltage. In this condition they cross the contact layer with the stiff and comparatively lower ionizing portion of their trajectory and the bulk of their straggling is done almost without fluctuations in the chip active volume.

8. TIMING STUDIES.

The HPD timing properties were studied with the following setup on the T2 model: the laser pulse was delayed with the help of a 200 m long (1 μs) optical fiber. The fiber stretched the light pulse to 2 ns FWHM. The light spot on the PC was smaller than 1 mm diameter. The laser light was attenuated until the HPD showed (on average) a 200 p.e. signal. The HPD signal was amplified by 2 cascaded amplifiers with a combined gain of 5000. The first amplifier had a nominal input r.m.s. noise of 15 μV resulting in a 75 mV output r.m.s. noise. The amplifiers were AC coupled to a CFD. The CFD was set at a threshold of 800 mV, producing a stop signal for the Silena MCA. The start signal of the MCA was provided by a fast photodiode (also excited by the laser pulse), discriminated and delayed by a timing unit set at 1 μs (300 ps nominal jitter at that setting).

The results are shown in figure 21. Most of the data is well fit by a 650 ps wide gaussian, while a few percent of the events were fit by an exponential with a 1.4 ns lifetime. These early triggers are probably due to the amplifier noise.

9. AGEING.

The demanding tests described in the earlier chapters were limited to small areas of the tubes T1 and T2. Uniformity tests on both tubes displayed no measurable damage or signal degradation in the used areas. This finding indicates that neither dramatic ion backscattering degradation of the PC nor bombardment damage to the silicon chip are present.

No damage on the silicon was expected because the silicon chips have already been tested in reference 2 and survived the bombardment of millicoulombs per square millimeters at 10 kV.

More questions were raised about PC survivability^{2,5}. A careful study of compatibility of PC and silicon was performed on two dedicated tubes in a standard PC testing facility. One of the tubes was electron scrubbed before PC assembly, the second was not.

Both tubes were illuminated for several days while being operated at 7 kV and their PC current was continuously monitored. The following tests were done :

- Illumination at $5 \cdot 10^{-4}$ Lux for 650 hours (0.325 Lux-hour). Both tubes presented PC quantum efficiency stable within 2% over the entire test.

- The first tube (well scrubbed) was illuminated at 20 Lux for 100 seconds (0.55 Lux-hour) without any change of PC quantum efficiency.

- The second tube (unscrubbed)

- 1) was illuminated at 0.2 Lux for 7 minutes (0.023 Lux-hour) without PC quantum efficiency changes,

- 2) was illuminated at 2 Lux and showed a decay to 97% within 2 minutes (0.067 Lux-hour) and to 93% after 8 minutes (0.267 Lux-hour) of illumination. The tube was then measured at low illumination levels: it recovered 1% per minute for the first five minutes and returned to 100% PC quantum efficiency after 15 minutes.

3) was illuminated 30 seconds at 20 Lux (0.167 Lux-hour) and showed a decay to 90% of PC quantum efficiency. Almost full recovery was observed 24 hours later.

It was concluded that a well scrubbed silicon diode does not damage the photocathode in the described conditions.

The observation of the PC decay in the unscrubbed tube can be explained as follows. The operation of the unscrubbed HPD diode causes a comparatively large outgassing, but at low light level the getter pump manages to soak up the gas. At high illumination levels the getter pumping speed is overwhelmed, the pressure builds up, the p.e.s start stripping the gas atoms and ensuing ions degrade the PC. This does not happen if the tube is well scrubbed.

It is interesting to note that even after extremely high light level illumination in the unscrubbed tube (20 Lux for 30 seconds) the PC shows remarkable self repairing properties.

10. CONCLUSIONS.

A magnetic field insensitive light detector with signal to noise characteristics similar or better than photomultipliers was developed and tested. This new detector has the potentialities to replace the photomultipliers not only in magnetic fields but also in general purpose service.

11. ACKNOWLEDGMENTS.

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A.C. and R.D. wish to dedicate this paper to the memory of Mirella Keller that tragically left our group.

12. APPENDIX : HPD GAIN SIMULATION.

An accelerated p.e. hitting on a silicon chip will penetrate a depth

$$d_{\text{tot}} = 3.10^{-10} V^{1.4} [\text{cm}] \quad (\text{A.1})$$

where V is the PC voltage in volts.

As shown in the zoom of figure 22, the portion, d_c , of the total penetration distance is spent in the dead contact layer. For gain production, only the part of the track spent penetrating the fully depleted volume of the diode, d_{ef} , is effectively producing electron/hole pairs.

For $\theta = 0^\circ$, (the axis convention and the angle definition are shown in figure 22) the depth of the dead layer, d_c , is calculated substituting the threshold value of the gain curve in the formula A.1. If the p.e. does not hit the silicon perpendicularly to its surface ($\theta \neq 0^\circ$), the signal is roughly proportional to :

$$d_{\text{ef}} = d_{\text{tot}} - \frac{d_c}{\cos(\theta)} \quad (\text{A.2})$$

- HPD gain simulation with transverse magnetic field :

If the magnetic field is perpendicular to the accelerating electric field ($E = E_y$; $B = B_z$), the p.e. will follow a cycloid curve and the impact angle can be calculated with the following formula:

$$\tan(\theta) = - \frac{v_x}{v_y} \quad (\text{A3})$$

where v_x [v_y] represent the speed component along the x [y] axis

$$v_x(t) = \frac{E}{B} (1 - \cos(\Omega t)) \quad (\text{A4})$$

$$v_y(t) = - \frac{E}{B} \sin(\Omega t)$$

where Ω is the Larmor pulsation.

The time at which the p.e.s reach the photocathode can be obtained by requiring that :

$$y(t) = \frac{mE}{eB^2} (\cos(\Omega t) - 1) = -d \quad (A5)$$

where e and m are the electron charge and mass.

combining A3, A4 and A5 it is obtained :

$$\theta = \frac{1}{2} \text{Arccos}\left(1 - \frac{ed^2B^2}{mV}\right) \quad (A6)$$

where V is the PC high voltage and d is the PC to silicon chip gap

The gain is then given by the formula :

$$G = G_{(B=0)} \frac{d_{ef}}{d_{ef(B=0)}} \quad (A7)$$

- HPD gain simulation with magnetic field of arbitrary direction:

The axis are oriented so that the electric field E is parallel to the Y axis and the magnetic field B is in the plane X - Y , as in figure 22.

Analogous to the former case, the impact angle can be calculated with the formula :

$$\tan(\theta) = \frac{\sqrt{v_x^2 + v_z^2}}{v_y} \quad (A8)$$

where

$$\begin{aligned} v_x(t) &= -\frac{E}{2B} \sin(2\phi) \sin(\Omega t) + \frac{eE}{2m} \sin(2\phi) t \\ v_y(t) &= -\frac{E}{B} \sin^2\phi \sin(\Omega t) - \frac{eE}{m} (\cos^2\phi) t \\ v_z(t) &= -\frac{E}{B} \sin\phi (1 - \cos(\Omega t)) \end{aligned} \quad (A9)$$

The time at which the p.e.s reach the photocathode can be obtained by requiring that the y trajectory length is equal to the gap between the PC and the silicon chip :

$$y(t) \approx -\frac{eE}{2m} \cos^2\phi \, t^2 = -d \quad (\text{A10})$$

The gain can be obtained by inserting A8 to A10 into A7.

FIGURE CAPTIONS.

Figure 1:

Schematic cross section of one of the HPD prototypes reported in this paper. Shown is an early version with Kovar (a magnetic material) silicon diode support structure.

Figure 2:

Typical HPD spectral response.

Figure 3:

Block diagram of the data acquisition system. The different branches of the signal flow are used alternatively and not in parallel.

Figure 4:

Gain curve of a HPD. The normalization was obtained measuring the PC current at 200 Volts positive bias. The top insert (left-hand and top scale) details the onset of the gain; the gain of 2 around zero PC voltage is produced by the silicon diode sensitivity to light. The bottom plot (right-hand and bottom scale) shows the real HPD gain versus PC high voltage. A linear fit over the high points of the distribution determines an effective gain threshold of 2.1 kV.

Figure 5:

Typical signal shape of T1 HPD for a ten millions p.e.s light pulse.

Figure 6:

Linearity measurement of HPD pulse amplitude (right scale, squares, bottom distribution) and pulse charge integral (left scale, triangles and circles, top and left distributions) versus light pulse amplitude. The two charge integral distributions do not line up because of different calibrations of two different measurement setups. No departure from linearity in pulse amplitude is found in the charge integral.

Figure 7:

Rise time (triangles, solid line), fall time (circles, dashed line) and FWHM time (squares, dotted line) of HPD pulses versus light pulse amplitude; black symbols refer to left-hand scale and empty symbols refer to right-hand scale.

Figure 8:

HPD signal shape at different light amplitudes for tightly focussed light pulses (0.1 mm diameter focus, 300 ps laser). From figure A to D the light intensity is increased each time by one order of magnitude.

Figure 9:

Prompt peak surface (circles) and total surface (black diamonds) for the family of signal shapes of figure 8. The two hand drawn lines indicate the linear and the power 0.75 behaviors.

Figure 10:

Rise time (triangles), fall time (circles) and FWHM times (squares) of T1 HPD versus the silicon chip bias voltage. The diode full depletion in this HPD is reached at 20 Volts.

Figure 11:

Pulse height uniformity scan across the T2 HPD diameter. The silicon chip diameter was 11.7 mm.

Figure 12:

HPD edge sharpness. The black diamonds describe the fine scan of the HPD edge response versus the distance from the HPD center (left side scale). The triangles are the differentiation of the response curve. The gaussian fit shows a sigma of 40 microns.

Figure 13:

Time uniformity scan. Constant fraction discriminated time delay distribution versus position. "A" measurement over the T1 HPD (8 mm diameter) and "B" measurement over the T2 HPD (11.7 mm diameter).

Figure 14:

Normalized T2 HPD pulsed response versus axial magnetic field intensity (magnetic and electric fields parallel, 10 kV PC voltage).

Figure 15:

A - Normalized T2 HPD pulsed response versus tilted magnetic field intensity (magnetic and electric fields at 30° , 10 kV PC voltage). The solid line represents a calculated signal response and not a fit to the data.

B - Calculated signal response of T2 HPD at 8 kV PC voltage to magnetic fields tilted 60° with respect to the HPD electric field.

Figure 16:

Normalized T2 HPD pulsed response versus tilted magnetic field intensity (magnetic and electric fields at 41.5° , 8 kV PC voltage). The solid line represents a calculated signal response and not a fit to the data.

Figure 17:

Normalized T2 HPD pulsed response versus crossed magnetic field intensity (magnetic and electric fields at 90° , 7 kV PC voltage). The solid line represents a theoretical signal response fitted to the data by changing the PC-to-chip gap thickness.

Figure 18:

Gain scan at constant chip bombardment angle versus PC high voltage. The gain threshold is found to be increased to 3.1 kV in these working conditions.

Figure 19:

Single Electron Response distributions of T1 HPD for excitations with 0.26 (squares) and 0.65 (black diamonds) p.e. per pulse.

Figure 20:

Response spectrum of T1 HPD obtained by substrating the two spectra of figure 19. The horizontal scale was shifted to bring the pedestal position to the origin. The data were fit with multiple gaussians describing the HPD multiple p.e. response (solid curve). The dash dotted gaussian is the function used to fit the first p.e..

Figure 21

Timing spectrum of an HPD. The signal is fit with a gaussian for $t > 2.5$ ns and with an exponential for $t < 2.5$ ns.

Figure 22:

Details and angle conventions of the p.e. trajectories used in the HPD gain calculations.

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- 8 The charge amplifier had the following characteristics: 300 electron R.M.S. intrinsic noise plus 0.6 electrons noise for each added picofarad, rise and fall time 2 microseconds, provided by A. Lanza of INFN Pavia.
- 9 The penetration depth x is calculated with the formula
$$x = 3 \cdot 10^{-10} V^{1.4} \text{ [cm]} \quad (V \text{ in volts})$$
The effective gain threshold point was defined as the intercept at zero gain of a linear fit taken over the measured points with voltage higher than 5 KV.
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Figure 1:

Figure 2:

Figure 3:

Figure 4:

Figure 5:

Figure 6:

Figure 7:

Figure 8-A:

Figure 8-B:

Figure 8-C:

Figure 8-D:

Figure 9:

Figure 10:

Figure 11:

Figure 12:

Figure 13-A:

Figure 13-B:

Figure 14:

Figure 15-A:

Figure 15-B:

Figure 16:

Figure 17:

Figure 18:

Figure 19:

Figure 20:

Figure 21

Figure 22: