An Evaluation of the New Compact Hybrid Photodiodes R7110U-07/40 From Hamamatsu in High Speed Light Detection Mode

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Abstract

The main parameters of hybrid photodiodes (HPD) are constantly improving. In the new 20 mm ø HPDs from Hamamatsu an avalanche diode (AD) serves as anode. Due to high gain of the used ADs the HPDs show a total gain of $6-8\times10^4$ at nominal HV. This allows one to use HPDs with very fast low-noise voltage amplifiers and to detect fast pulses (down to the single photoelectron level) with very good amplitude resolution. Of a special interest are HPDs of the type R7110U-40 with $GaAsP$ photocathode which provide a quantum efficiency of ~ 40 % in maximum at ~ 500 nm. Results on the evaluation of the above mentioned HPDs and their comparison with HPDs from INTEVAC will be presented.

1 Introduction

HPDs, a combination of a vacuum tube with photocathode and of an electron bombarded diode as anode, are maturing. Photoelectrons ($ph.e.$) accelerated in a few keV electrical field and focused onto a semiconductor diode generate sufficient number of secondary electrons to be detected well above the noise when using charge sensitive preamplifiers and μsec filter amplifiers. Very good amplitude resolutions could be achieved (for pulses of up to ~ 10 $ph.e.$ content) in such devices (see, for example, [1]). Unfortunately in very fast low light level applications (demanding $nsec$ resolution) the gain of such tubes is not sufficient to resolve a few $ph.e.$ amplitudes. The reason is the following: an accelerated $ph.e.$ from the photocathode creates a couple of thousand electron-hole pairs in the active volume of the diode. In order to provide a single $ph.e.$ amplitude resolution this signal charge must exceed the noise of the following preamplifier by a factor of ≥ 6. For example, assuming that a single $ph.e.$ creates ~ 2000 electron-hole pairs in the diode one can estimate that the

$r.m.s.$ noise of the preamplifier should not exceed $\sim$ 300 electrons. In reality a wide-band (i.e. very fast) preamplifier has at least an order of magnitude higher noise than the above estimated level. In order to stay well above this noise one has to sacrifice the bandwidth of the preamplifier i.e. to make the response much slower. By replacing the diode by one with (sufficient) internal gain such as an avalanche diode one can cure the above mentioned problem. With such a device it is possible to conserve both the fast time response and the very good amplitude resolution of the HPD.

2 INTEVAC HPDs with $GaAsP$ Photocathode

In the previous report on prototype INTEVAC HPDs with 18 mm ø $GaAsP$ photocathode and $GaAs$ Schottky AD it was shown to achieve multi-$ph.e.$ resolution with a fast charge sensitive and transimpedance preamplifiers and filter time constants down to 20 $nsec$ (resulting in a pulse FWHM of $\sim$ 50 $nsec$) [2]. Part of this limitation in speed was due to the use of very fast but low gain (typically 6-8) GaAs ADs in these tubes. The HPDs from INTEVAC provide QE of 40-45 % in the wavelength range 460-600 nm. By using the WLS technique it was possible to enhance their QE to the level of $\sim$ 25 % in the near UV part of the spectrum [2]. The fact that the latter value was lower than the QE at maximum was due to the large $h/d = 6mm/18mm$ ratio of the input glass window (here h is the thickness and d is the diameter). Note that in order to provide efficient trapping of the shifted isotropic light one has to provide much lower h/d ratio (see, for example, [2]).

3 New Compact HPDs from Hamamatsu

Recently HPDs including Si AD became available from Hamamatsu providing an overall gain of up to few times 10^4. Such a high gain of the HPDs allows one to replace the charge sensitive preamplifier-filter amplifier combination by a fast, low noise transimpedance or even a voltage preamplifier and to provide high response speed and very good amplitude resolution simultaneously. Here we report on the study of two prototype HPDs, one with multialkali (type R7110U-07) and another one with $GaAsP$ (type R7110U-40) photocathode from Hamamatsu (along with INTEVAC HPD the latter is the second commercially available light sensor with very high QE $GaAsP$ photocathode). The R7110U-07 has a photocathode of 8 mm diameter and the R7110U-40 has a 6×6 mm^2 (effective 5 mm ø) photocathode. Both HPDs include a 3 mm ø Si ADs as anode and are of electrostatic focusing type. Some characteristics of the tube R7110U like its behavior in magnetic field and the amplitude response have been reported in [3] and a more extended version is presented in [4].

4 Measurements

Measurements were done in the so-called high speed light detection mode recommended by Hamamatsu (see the data sheet of R7110U HPDs). The HPDs were operated under cathode to anode potential of 8 keV and the AD applied voltage of $150-160V$ (providing gain of ~45). We used a fast blue LED (Nichia NLPB320A, $\lambda_{max}\sim$ 450nm) light pulser (provides pulses of $\sim$ 4 $nsec$ FWHM) of adjustable intensity as light source. The signal from HPDs were fed into commercially available fast MMIC preamplifier from Hewlett Packard of INA-02170 type (voltage gain 31.5 db, NF=2 db, bandwidth 1 GHz).

4.1 Amplitude Resolution

For the measurements on amplitude resolution we used a multichannel analyzer LeCroy model 3001 in charge measuring mode with external gates of 15-20 $nsec$ width. In Fig.1 one can see an example of the measured multi-*ph.e.* resolution of the tube R7110U-40. In this measurement the light pulser intensity was adjusted to generate on average $\sim$ 2.2 *ph.e.* per pulse. The first peak is the pedestal. With both R7110U HPDs we could clearly resovle multi-*ph.e.* pulses of up to 4-5 *ph.e.* content. The relative amplitude resolution of the single *ph.e.* distribution can be described by $\sigma_{gauss.}\sim$ 22 %.

4.2 Gain

By measuring the single *ph.e.* response of the R7110U-40 HPD and the gain of the preamplifier and by using the known sensitivity of the used ADC we determined the total gain of the tube to be $\sim 8.3 \times 10^4$ at the nominal applied cathode-anode HV of 8.0 kV and the AD applied voltage of 160 V (the breakdown voltage of the AD was 162 V). When lowering the HV down to 6.0 kV we measured a gain of 5.8×10^4. From these two measurements one can estimate a *ph.e.* energy loss of $\sim$ 1.5 keV in the passive layer at the AD window. This means that at nominal HV of 8.0 keV a *ph.e.* from the photocathode creates $(8.0 - 1.5)keV/3.6eV \sim 1800$ electron-hole pairs in the active volume of the AD. The gain of the latter was estimated to be $\sim$ 46 at the applied voltage of 160 V.

4.3 Speed

Studies a with a fast digital scope (Tektronix 520B, 2 Gsamples/s) showed pulse rise times of 3-4 *nsec*, fall times of 7-8 *nsec* and pulse FWHM of ∼8-9 *nsec* (see Fig.2). This has been measured for single *ph.e.* and is therefore free of the time spread of the light pulse as well as from possible transit time spread in the HPD. Due to the very good amplitude resolution of the HPDs, at very low light levels one observes pulses of only discrete amplitudes on the oscilloscope. For example, three pulses on Fig.2 correspond to one, two and three *ph.e.* amplitudes.

4.4 Afterpulsing

Afterpulsing is an unwanted effect in all types of vacuum light sensors. It can set a high trigger threshold in light detectors operating in self-trigger mode at a presence of a relatively high light background such as, for example, atmospheric Cherenkov telescopes [5]. Afterpulsing is especially hazardous for light sensors which operate under applied potential difference of many kVs. Any substantial rate of heavy ions bombarding the photocathode with a kinetic energy of, for example, 8 keV can bring to its degradation and eventually can destroy it. In HPDs in order to prevent ions to fly back to the photocathode usually a system of screening baffles and in some cases also a conducting finger set close to the anode, are used (see for details [2] and [6]). Recently an interesting general solution to overcome the afterpulsing in HPDs have been proposed in [6] and [7]. We studied the afterpulsing features of the new HPDs with a digital scope in the pulse superposition mode. On Fig.3 and Fig.4 are shown the results of afterpulsing rate measurements for both HPD types. The LED trigger rate was set to $\sim$ 1 kHz during these measurements and the data have been accumulated for the duration of three minutes. It is interesting to note, that the R7110U-40 tube with $GaAsP$ photocathode shows much lower afterpulsing rate ($\leq 10^{-5}$) compared to that of R7110U-07 ($\leq 5 \times 10^{-4}$) with multialkali photocathode (compare Fig.3 with the Fig.4). In both measurements we adjusted gain of the HPDs to provide 50 mV/*ph.e.*. One should mention that the production and the manufacturing of $GaAsP$ photocathodes in HPDs is a rather sophisticated process and is quite different from that of conventional multialkali photocathodes. One can speculate, for example, that the Cs activation of the $GaAsP$ photocathode, unlike the multialkali ones, takes place outside the HPD tube which in turn results in a much lower afterpulsing rate.

4.5 Quantum Efficiency

We measured the quantum efficiency (QE) of the tube with $GaAsP$ photocathode (see Fig.5). For this purpose we used a spectrophotometer Beckman-35 in combination with a picoammeter Keitley-485. The QE of the tube was normalized to that of a 10×10 mm^2 calibrated photodiode from Hamamatsu (type H3590-003, serial number 03) used in the photovoltaic mode. One can see on Fig.5 that this tube shows $\geq$30 % QE for wavelengths in the range 430-630 nm and its peak value is 39 % in maximum at $\sim$ 520 nm. We estimate an error of $\leq$ 5 % for these measurements.

4.6 Enhanced QE in the Near UV by Using the WLS Technique

By using the wavelength shifting (WLS) technique we have conducted some simple tests in order to enhance the QE of the R7110U-40 tube in the near UV part of the spectrum. Two types of WLS dyes were used in these tests, the first one was the fluorescent dye BASF 083 (blue) and the second one BASF 241 (yellow). The WLS were embedded in plexiglas in the form of 3 mm thick plastic sheets (in fact these were wavelength shifting bars for scintillation sampling calorimeter). For our tests we cut small pieces of WLS plexiglas in the form of truncated pyramids of 45 degree opening angle, with the base size of 6×6 mm^2 and the hight of 1.5 mm. The side walls of pyramids were not polished and we painted them with white diffuse reflecting paint (with Tipp-Ex in fact) in order to enhance the light collection efficiency. After that the samples were put into optical contact with the HPD input window and we measured the QE. The results are shown on Fig.5. Indeed one can observe enhanced QE in the wavelength range below 400 nms. The blue WLS dye provides an enhanced QE in the range of 10-20 % for wavelengths 290-400 nms while for wavelengths above 400 nms it essentially repeats the original QE shape of the HPD. Unlike the blue WLS dye the yellow one provides more complicated shape with three peaks and two valleys (in the original WLS design the dye concentration is too low to absorb fully the light). While it provides an enhancement of QE to $\sim$ 8-22 % for wavelengths 250-400 nms, it lowers the original QE of 20-37 % to the level of 13-15 % in the wavelength range 410-540 nm (it effectively absorbs light in the latter region but re-emits it at longer wavelengths which is not optimally matching the sensitivity of the HPD). These simple tests again demonstrate that by using the WLS technique one can substantially enhance the QE in the near UV part of the spectrum (see [2]). The proper choice of the fast WLS dye and its fine tuning can provide high efficiency in boosting the QE at short wavelengths. An important step which can help to utilize most of the shifted light is connected with the input window geometry i.e. one needs substantially lower h/d ratio. For the given window thickness one can achieve the latter by producing, for example, larger diameter *GaAsP* photocathodes which may widen the range of applications of such HPDs.

5 Conclusions

From our studies the following conclusions can be drawn:

- one can achieve a multi-*ph.e.* amplitude resolution at very low light levels in high speed light detection mode with both types of new R7110U HPDs.
- thank to high gain of R7110U HPDs one can feed their signals into commercially available low-cost wide band MMIC voltage preamplifiers, the output of which preserves the tube's original speed and the amplitude resolution.
- a low rate of afterpulses was observed in the R7110U-40 HPD with *GaAsP* photocathode confirming the earlier observations made with similar type but larger size INTEVAC tubes. The reason can be the unconventional production and manufacturing process of *GaAsP* photocathodes.
- by using the WLS technique one can enhance the QE of R7110U-40 HPD in the near UV part of the spectrum. In order to maximize the QE in the near UV one has to provide thin, relatively large diameter input windows for optimal light trapping.
- probably one can significantly better the time response of R7110U HPDs by improving the anode (AD) part.

It should be noted that particularly the HPDs with *GaAsP* photocathode open a field of highly efficient photon detection in the visible spectral range with *nsec* speed and multi-*ph.e.* amplitude resolution. This will probably lead to a significant progress in many disciplines relying on fast low light level measurements.

References

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Figure Captions

Fig.1. The amplitude resolution of the R7110U-40 HPD. The light level is adjusted to provide 2.2 $ph.e.$s in the mean. The first peak is the pedestal.

Fig.2. The time response of the R7110U-40 HPD measured in high speed light detection mode. Three pulses correspond to amplitudes of 1, 2 and 3 $ph.e.$s.

Fig.3. The afterpulsing rate of the R7110U-07 HPD. The LED trigger rate was set to 1 kHz and the integration time was 3 minutes.

Fig.4. The afterpulsing of the R7110U-40 HPD. The LED trigger rate was set to 1 kHz and the integration time was 3 minutes.

Fig.5. The measured QE of the R7110U-40 HPD with $GaAsP$ photocathode without (solid line) and with application of WLS dyes (dashed line:HPD+BASF 083; dotted line:HPD+BASF 241).

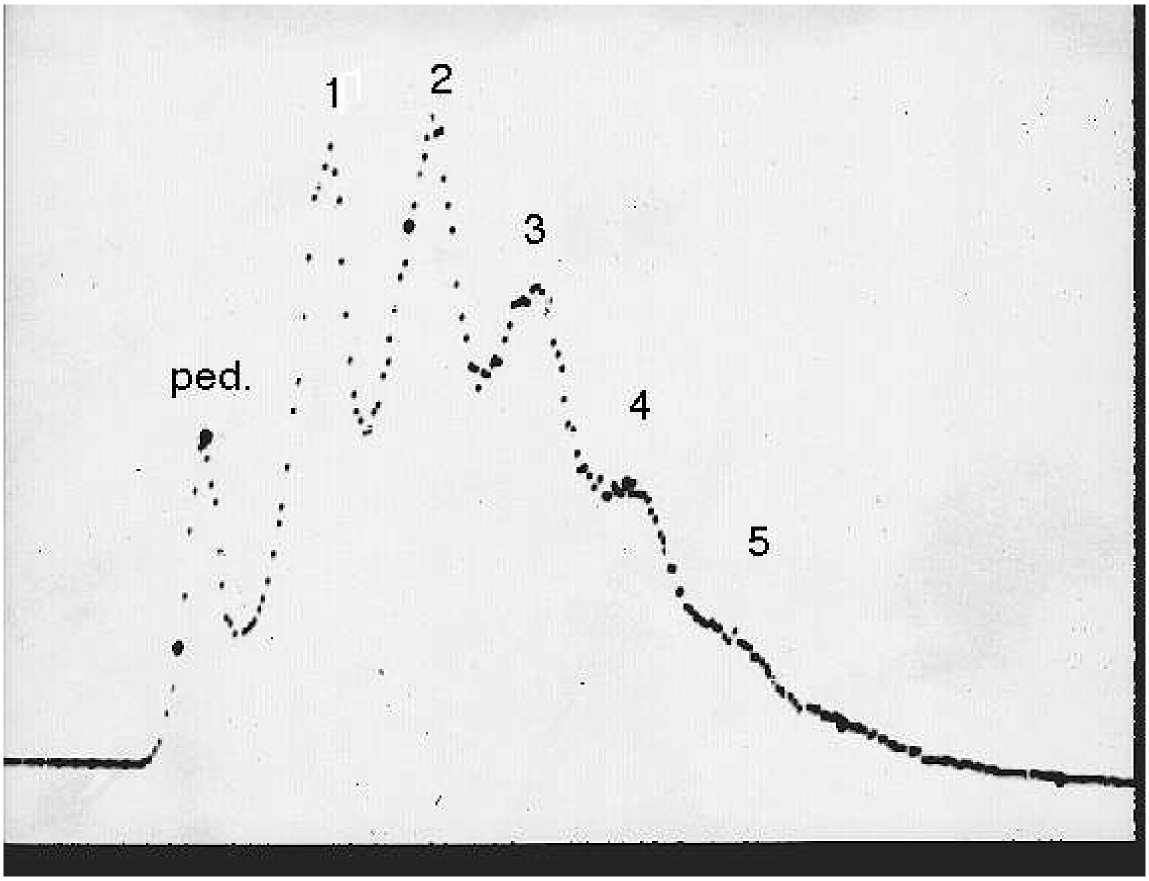

Fig. 1.

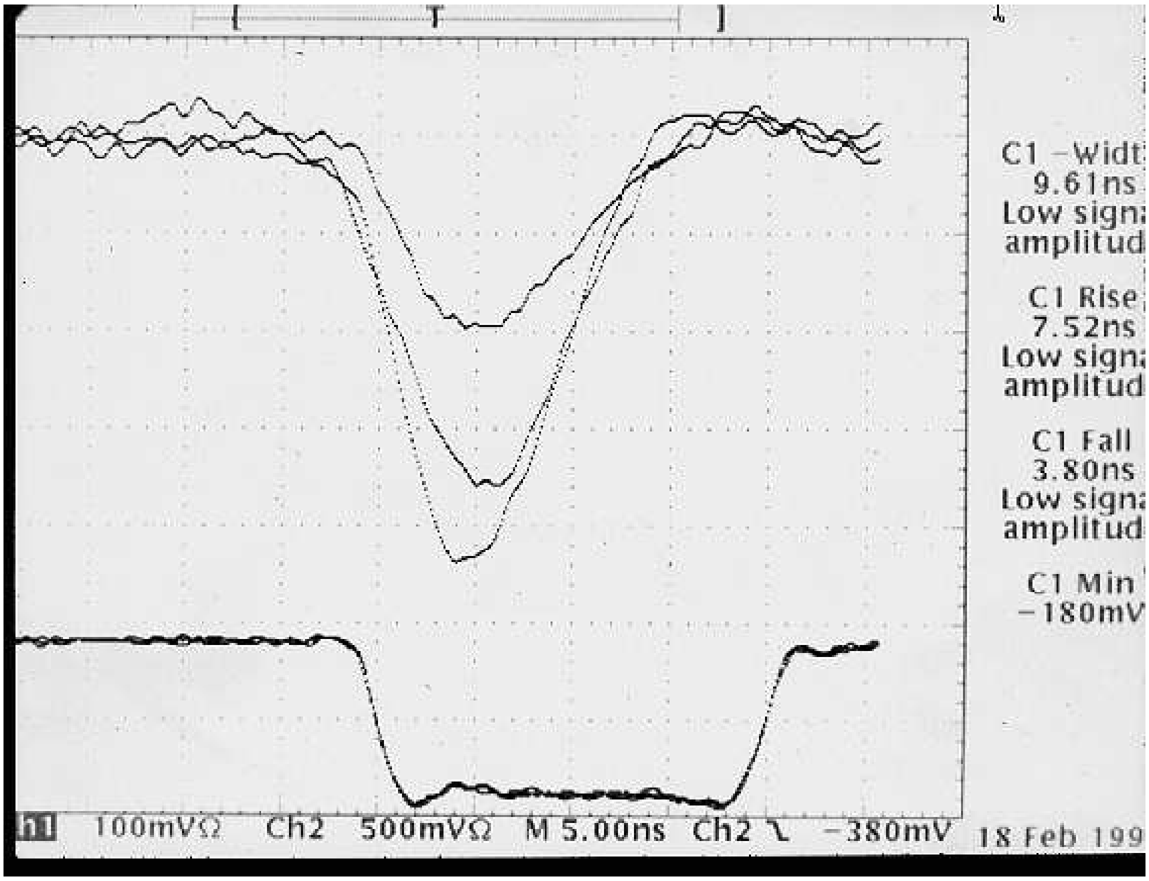
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Fig. 2.

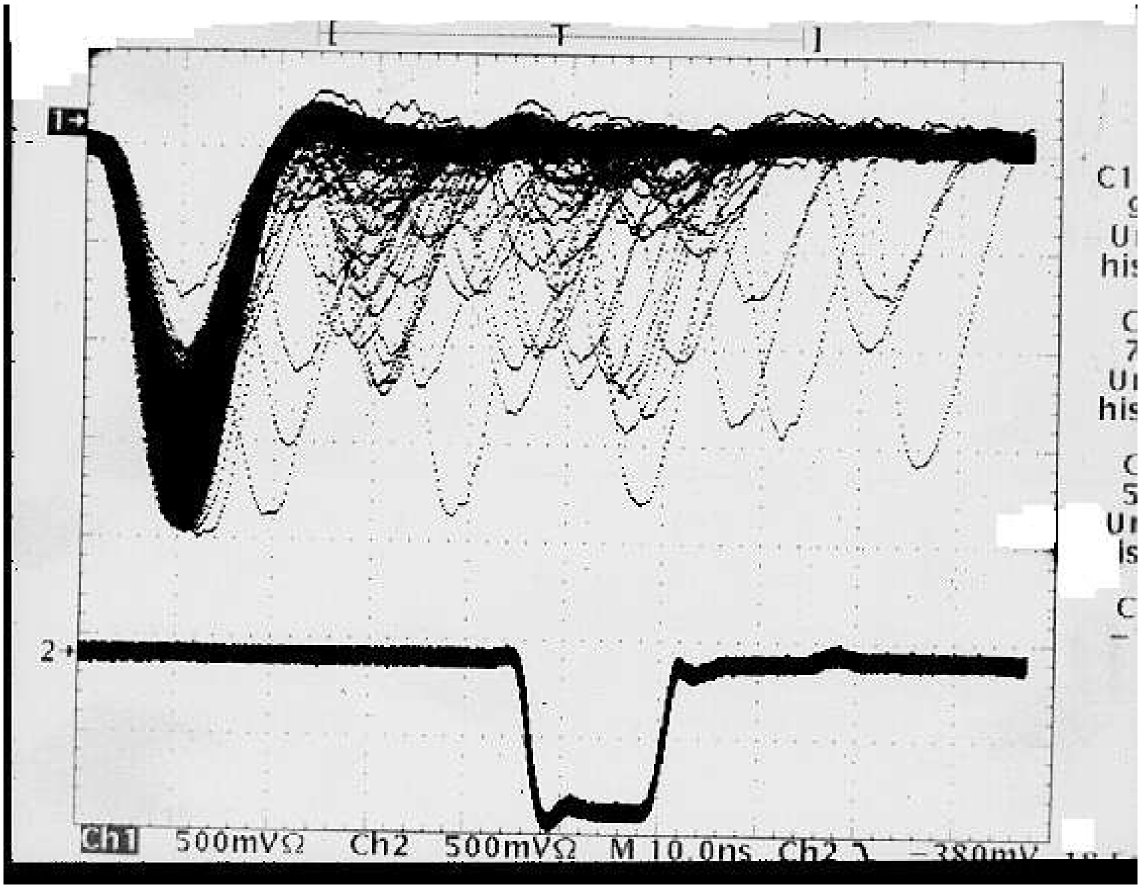

Fig. 3.

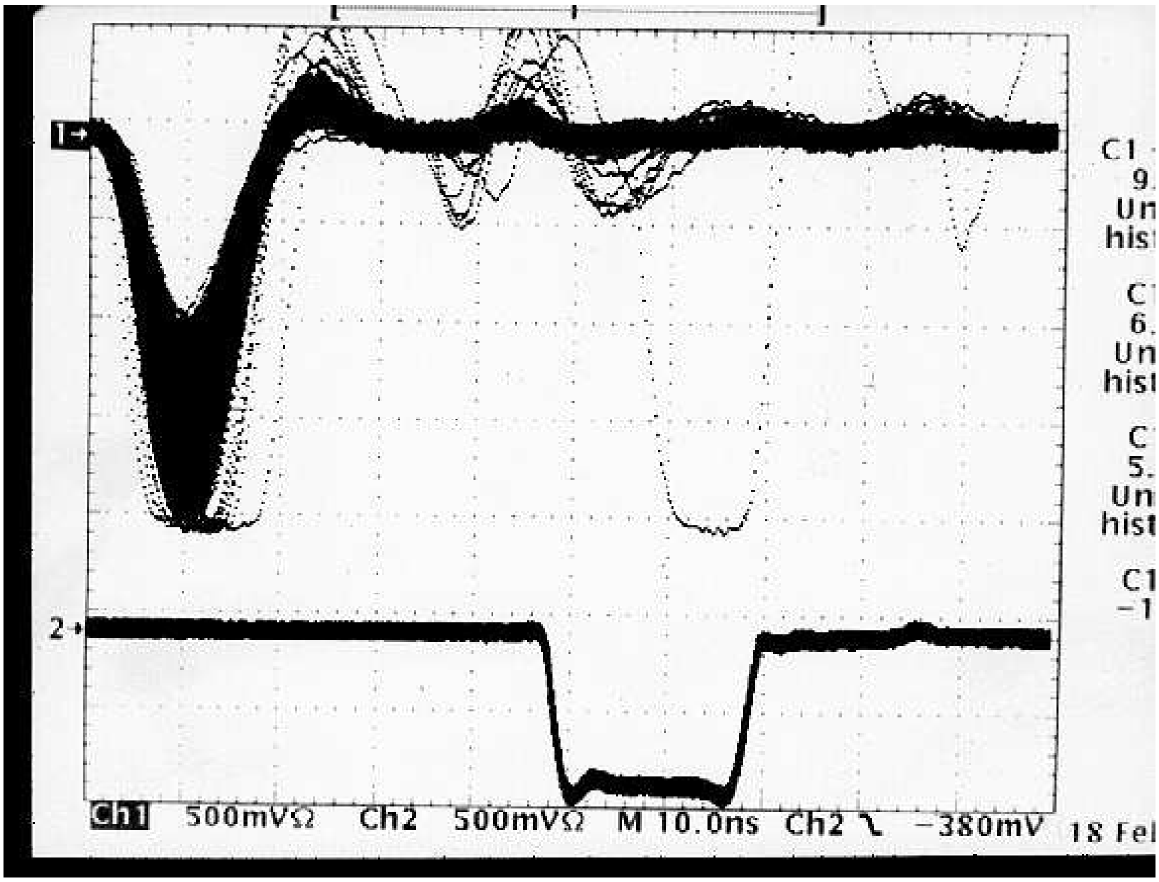

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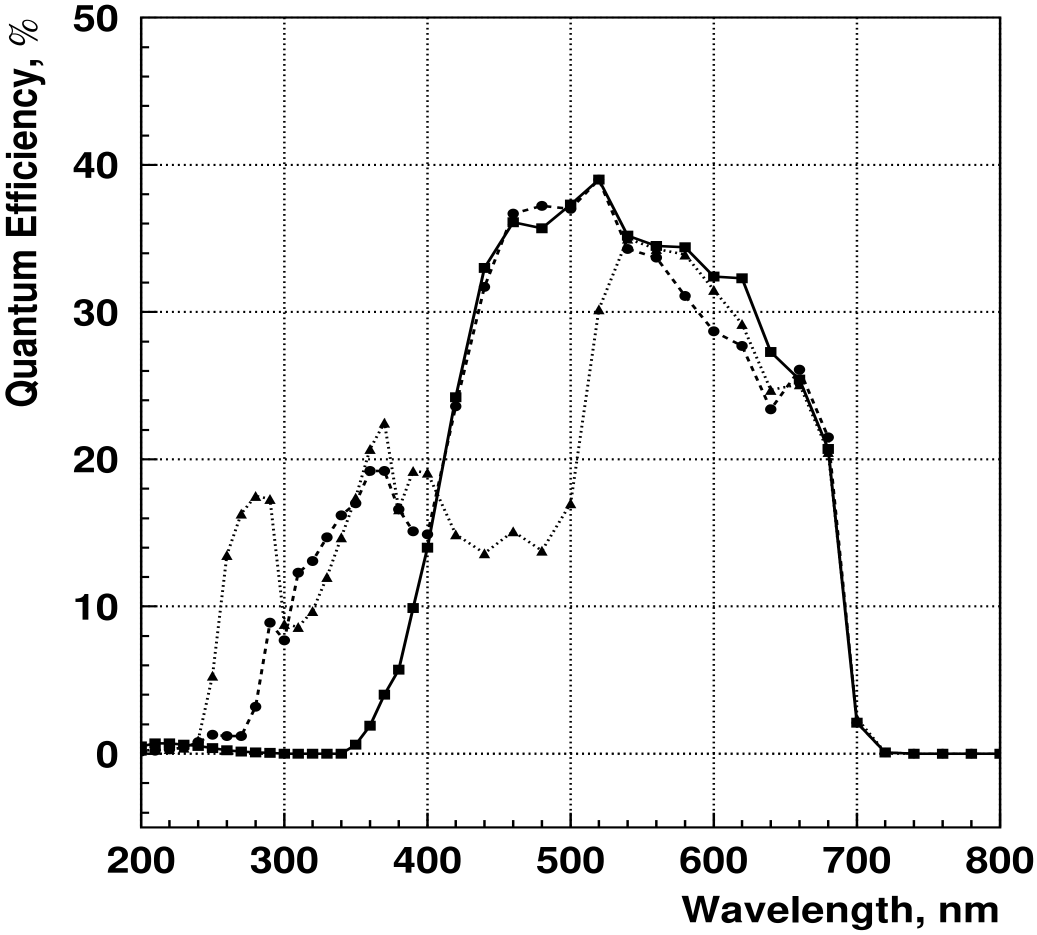
Fig. 4.


Quantum Efficiency, %
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200
300
400
500
600
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Wavelength, nm

Fig. 5.