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Visible Light Photon Counters optimization for quantum information applications

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Abstract

In this paper we describe the studies of the main parameters needed for optimal operation of Visible Light Photon Counters (VLPCs) when used in quantum information systems. The isolation of the single photon signal is analyzed through the definition of a *contamination* parameter. A compromise in the minimization of this parameter for temperature, bias voltage and dark count variation must be achieved and this depends on the experimental conditions.

Visible Light Photon Counters (VLPC) [1] [2] are silicon devices composed of an undoped intrinsic silicon layer that overlays a weakly compensated arsenic-doped gain layer. With this configuration the silicon contains not only the 1.12 eV gap between the valence and conduction band, but also a 0.05 gap between the conduction and the impurity band. Fig. 1 shows the energy levels of the VLPC detector. A photon typically creates an electron-hole pair in the intrinsic region, under the applied bias the electron moves to the left being collected at the front contact. The positively ionized donor (called D^+ or hole) moves to the right gaining kinetic energy and loosing it again in a series of scattering events too weak to produce any impact-ionization across the 1.12 eV gap. After reaching the As-doped region, the hole needs only 0.05 eV of kinetic energy to impact-ionize an As atom and generate an electron-D^+ pair. The electron liberated will move to the left and will impact-ionize a second As atom liberating another electron-D^+ pair which will repeat the process creating what is called avalanche multiplication.

At low operating temperature the thermal generation of the electron-hole pairs in the 1.12 eV gap is negligible. If they are generated in the left part of the As doped region the electron will contribute to the background *dark current*, but if the electron-hole pair were generated in the right hand portion of the As doped region, they will contribute to the *dark count* pulses that are indistinguishable from those initiated by the photons.

The current generated for each VLPC pixel is collected at the front contact and is then amplified, integrated and digitalized. A charge distribution from a pulsed LED light source is shown in Fig. 2. The distribution shows a series of peaks. The first peak is the zero photon event or pedestal which is generated by electronic noise. The one photon peak, and the remaining peaks correspond to the different photon numbers. The spectra were fitted using the model proposed in Ref.[3]:

$$P(q) = \sum_i (p_i^\alpha/(2\pi\sigma_i)) \exp -\frac{(q-\mu_i)^2}{2\sigma_i^2} \tag{1}$$

where $P(q)$ is the probability of measuring a charge q in the ADC, p_i^α is the probability for obtaining the integer i photons ($i = 1, 2, 3, ...$) in a Poisson distribution with mean α, μ_i is the position of the peak corresponding to i photons calculated as $\mu_i = \mu_0 + i * g$ (where g is the gain in units of ADC/e, while μ_0 is the position of the pedestal determined by the electronics), and σ_i is the RMS of the i^{th} peak in the distribution (a detailed study of σ_i is presented in Ref.[4]).

The capability of the VLPC to distinguish single photons makes them an ideal detector to be used in quantum information applications as discussed in Refs. [5], [6] and [7]. In these applications one needs to isolate the single photon peak from the rest of the spectrum without introducing contamination that can come from the neighboring peaks or from the dark counts. This could be achieved by making a selection in q, and keeping only those events with $(\mu_1 - n_1\sigma_1) \leq q \leq (\mu_1 + n_2\sigma_1)$, where n_1 and n_2 should be selected to obtain the optimal separation between the single photon peak and the rest of the distribution. In order to do this optimization we propose to construct a magnitude η that can measure the contamination in the one photon peak due to the pedestal, plus the counts coming from the second, third and higher photon signals. It can be defined as:

$$\eta = \int_{\mu_1 - n_1\sigma_1}^{\infty} P_{ped}\, dq \, + \int_{-\infty}^{\mu_1 + n_2\sigma_1} P_{i\geq 2}\, dq \tag{2}$$

where P_{ped} is the first term ($i = 0$) in the sum at the right hand of Eq.(1), and corresponds to the counts coming from the pedestal peak that contaminates the single photon peak. $P_{i\geq 2}$ represents the sum of the terms with $i \geq 2$ in Eq.(1). The integration is over the ADC counts represented by q. The limits in the integration n_1 and n_2 indicate the area allowed for the one photon peak, such that all the events outside this region are excluded.

We studied the contamination of the VLPC detectors through the data obtained by the VLPC team of the DØ experiment [8] at Fermi National Accelerator Laboratory. The gain, relative quantum efficiency (QE) and dark-current count rates were measured for 100,000 channels of VLPC pixels under several different operating conditions [9].

Our observations show that the QE increases as the temperature of the device increases. In previous work [7] this effect has been attributed to the dielectric constant increase in the gain region of the VLPC. Our measurements also show that the contamination coming from the pedestal peak increases with temperature (due mostly to an increase in the dark current). Both effects can be seen in Fig. 3 for different operating voltages.

In order to minimize the contamination coming from the pedestal peak, we must find the minimum value of the dark counts keeping the QE as high as possible when the temperature and voltage change. From Fig. 3 we can see that for this system the optimal values for the temperature and the voltage are T = 8 K and V = 7.3 V respectively. These values yield a contamination of 0.2% with a relative QE of 90% when using the $n_1 = 3\sigma$ limit (which yields a 99% acceptance effiency for single photon events). The width of the integration window in accepting the signal coming from the VLPC also plays a role in the amount of the contamination in the system. If it is set to larger values, the ADC will count more dark current, adding more noise to the signal in this way. For this reason it is desirable to keep this value as small as possible. The value used by the DØ test stand was 120 ns to match with the requirements of the DØ electronics, but for a smaller system it can be as low as 20 ns.

The contamination can be reduced to 0.1% by restricting the area of the one photon peak from 3σ to 1σ, but in this way we reduce the acceptance of the signal from 99% to 66%. Another source of contamination is the electronic noise (measured as the width of the pedestal peak), which varies from one detection system to another. We simulated the effect of a noisy detector by doubling the amount of noise measured for the DØ test stand, as shown in Fig. 4. In the same plot we show the effect of using 3σ or 1σ for the background limit.

The contamination coming from the two, three, four and remaining peaks was calculated numericaly using the second term of the right hand side of Eq.(2). Fig. 5 shows the contamination when the numbers of photons arriving on the VLPCs increases. It is clear that the area of the peak chosen for the one photon signal is critical, since the change in the limit n_2 from 1σ to 3σ increases the contamination by a factor of 100.

In conclusion, we have presented studies done with VLPC operating parameters in order to minimize the contamination in the single photon peak needed for quantum information experiments. The contamination will depend strongly on the choice of the area for the single photon peak, and the noise level of the detection system. A compromise in the selection of these values allows one to increase the acceptance of single photons, or to reduce the contamination of the sample, thus, producing a much cleaner single-photon data sample at the expense of lower detection efficiency. For our system, the optimal operation parameters found with the method proposed were $V = 7.3$ V and $T = 8$ K. The area limit chosen for the 0_{th} peak was $n_1 = 3\sigma$, and the limit for the higher peaks was $n_2 = 2\sigma$. The total contamination found through Eq.(2) is 4.2% with a relative quantum efficiency of 90% and a probability of accepting the single photon signal of 95%.

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Figures

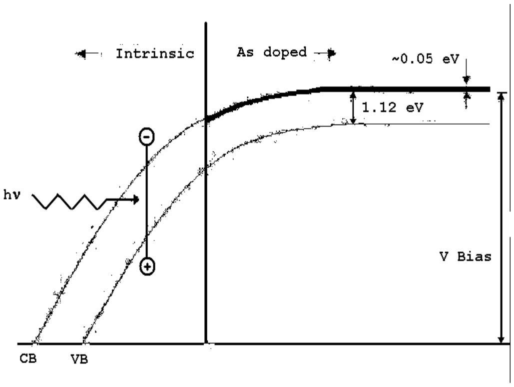

Figure 1: Energy diagram for the layers of a VLPC between the front contact (at the left), and the back contact (to the right) [1].

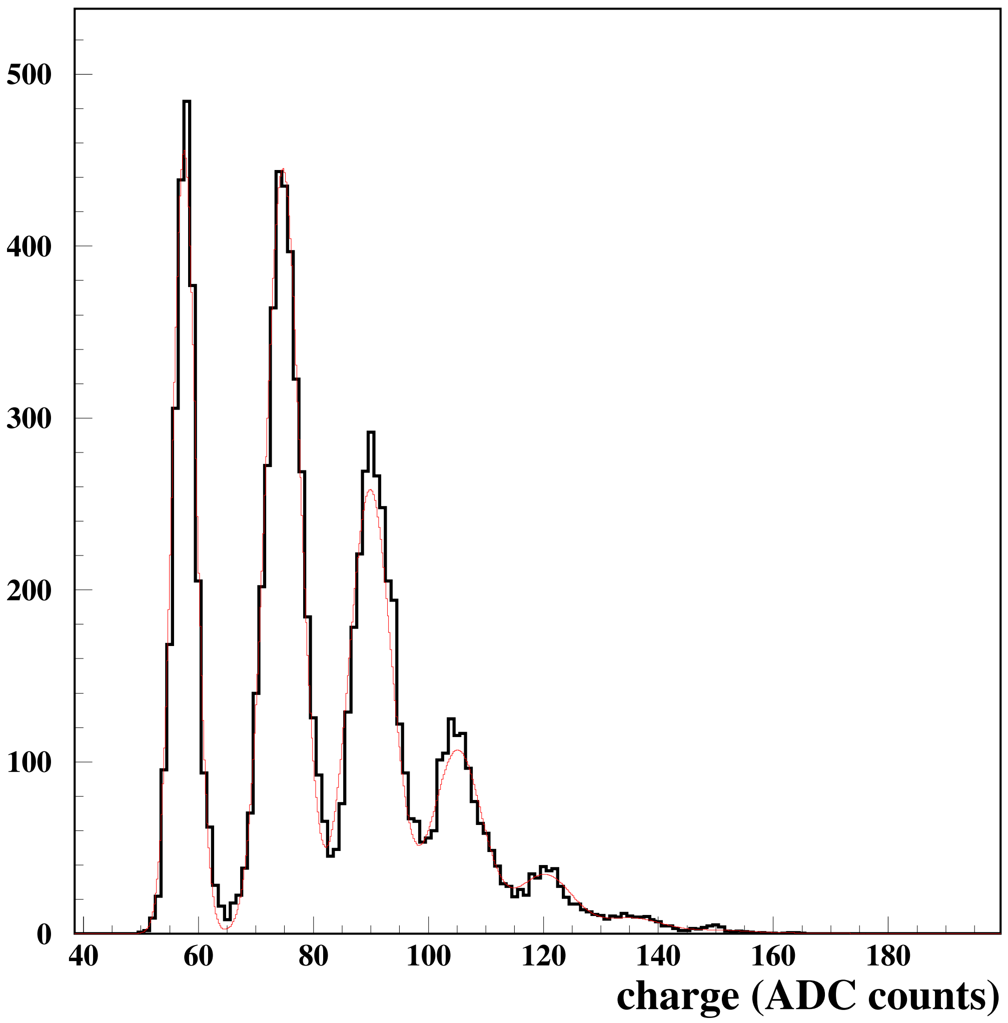

Figure 2: Charge distribution from a VLPC pixel operated at 6.8 V and T=9K. The open histogram corresponds to data (10,000 entries) and the curve corresponds to a fit using equation 1.

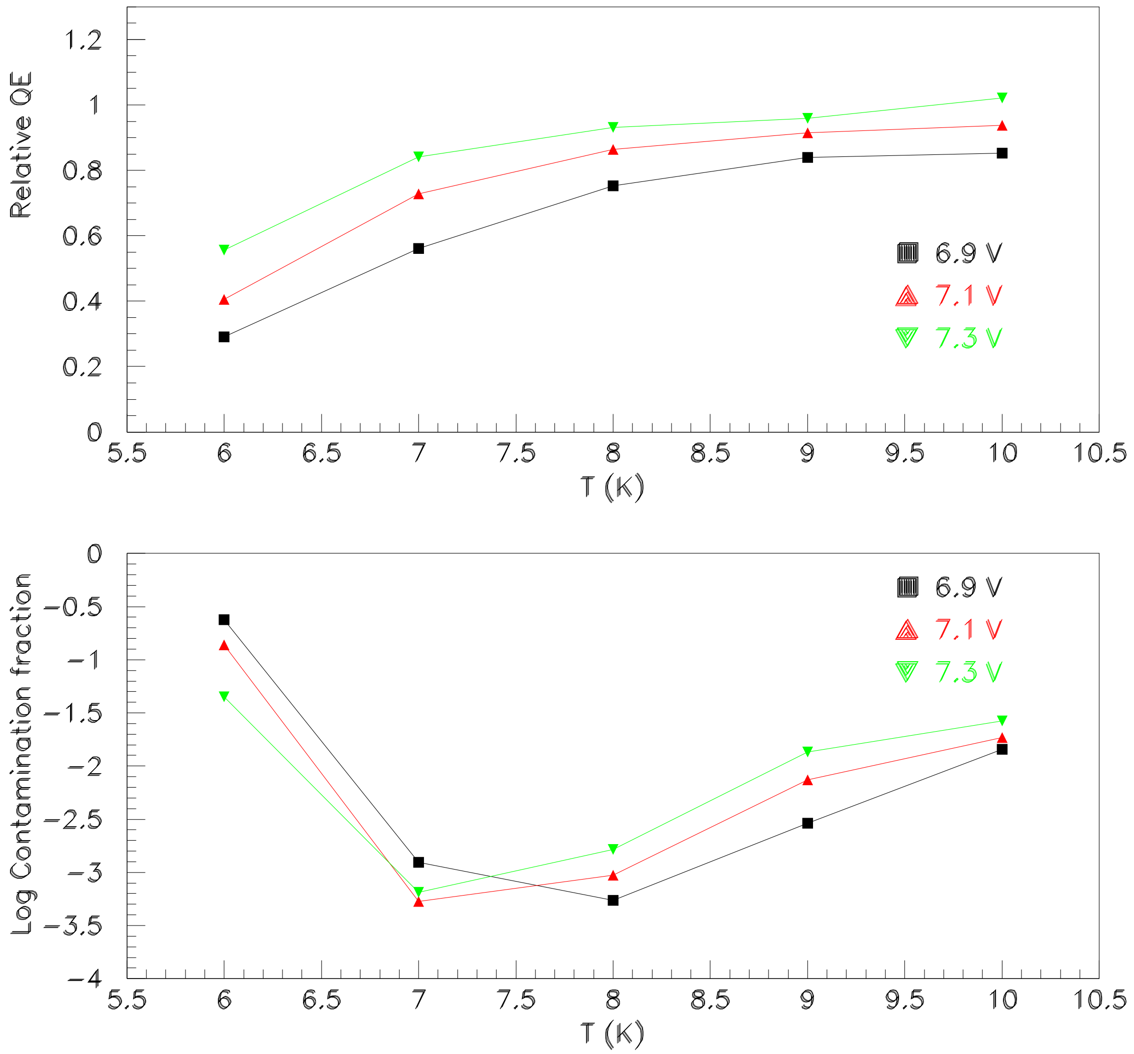

Figure 3: Variation of the relative quantum efficiency and the contamination introduced by the pedestal in the one photon peak. The relative QE was measured by the DØ test station by keeping the current in the LED fixed while changing the temperature and bias voltage, while the contamination was calculated using the first term of the righ hand side of Eq.(2).

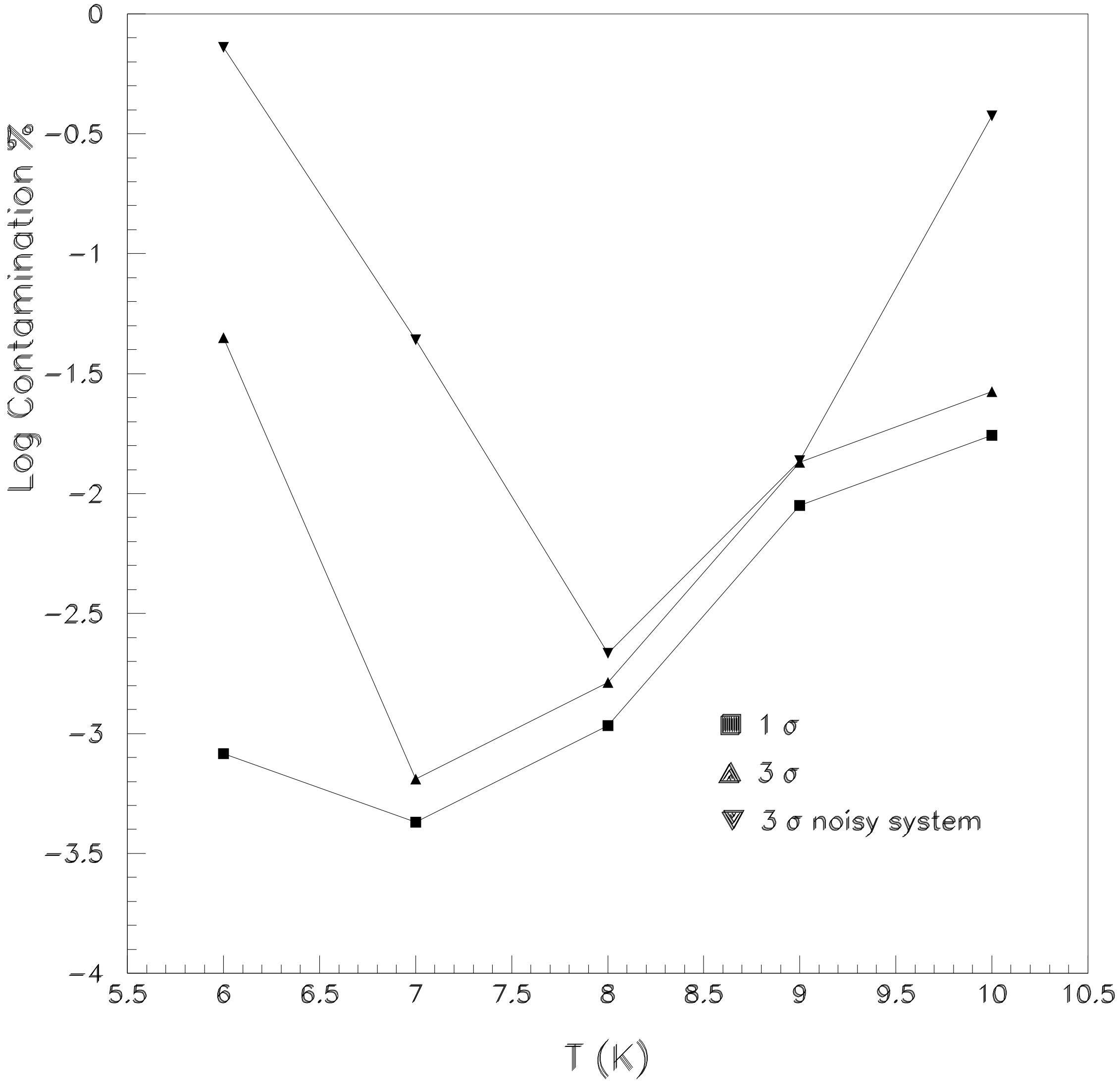

Figure 4: Variation of the contamination with respect to temperature for two values chosen for the signal noise limit. Also shown is the effect of contamination when a noisy system is used.

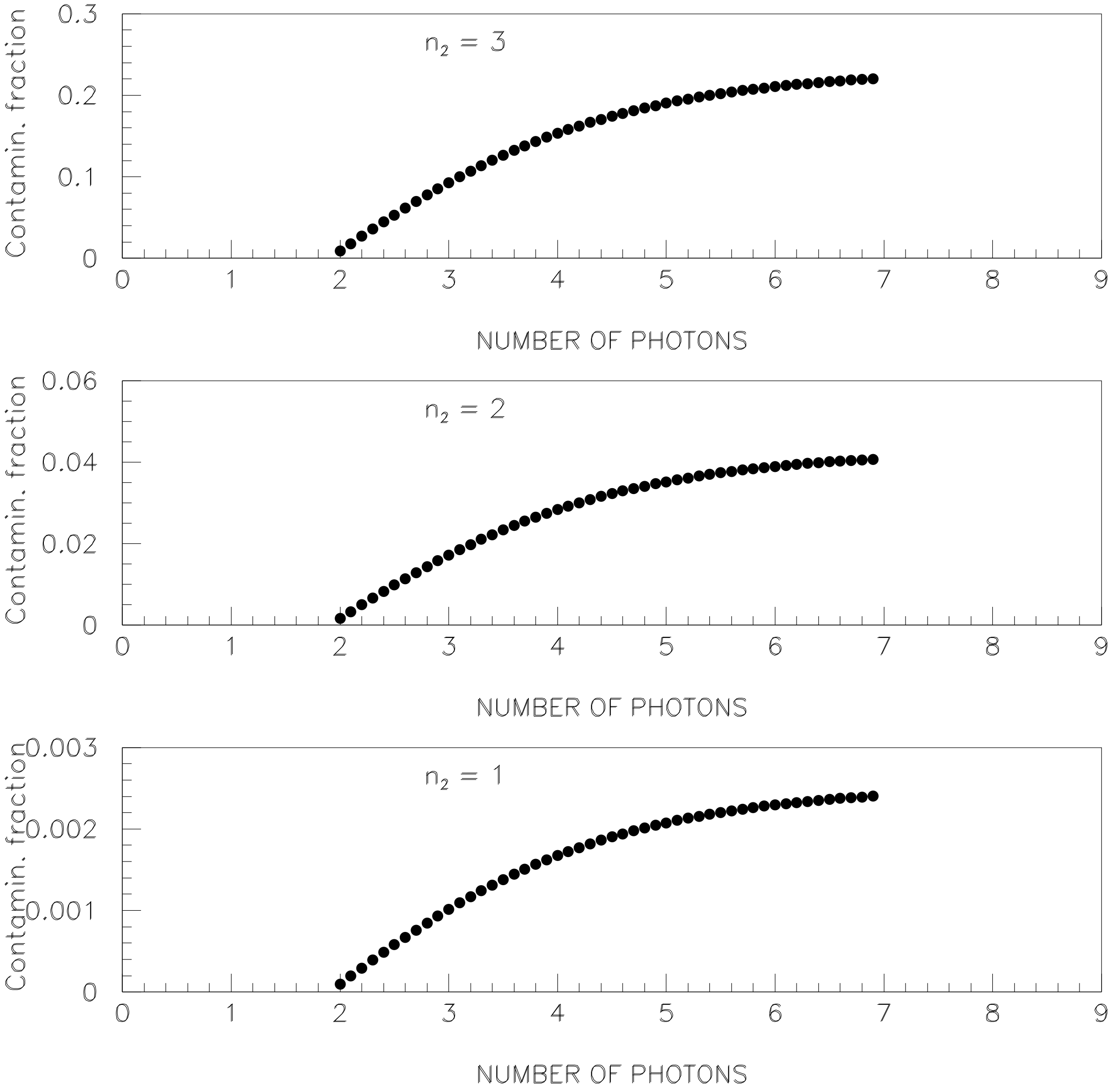

Figure 5: Contamination fraction suffered by the single photon peak when the amount of incident photons changes from the second until the 7th peak. Note the reduction of the contamination by a factor of 10 for each area limit used for the single photon peak