Photodetectors and Power Meters II

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Germanium quad-cell for single photon detection in the near infrared

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ABSTRACT

We report the first results obtained with a germanium quad-cell sensor operated in Geiger-mode regime. After a quantitative characterization of the single pixel, both in counting and in timing applications, we quantitatively assess the intensity of the optical coupling among the detectors of the cell due to secondary photon emission from hot carriers. This effect, intrinsically related to Geiger-mode operation, has been overcome by sequentially driving the pixels of the cell. A preliminary test demonstrates the tracking capabilities of the sensor. Since the single pixel can detect the arrival time of the photon with a precision better than 100ps FWHM, arrays of such devices could be also employed in wavelength and timing resolved luminescence measurements in the near-infrared.

Keywords: photon counting, avalanche photodiodes, detectors, array, near-infrared detectors, photon timing.

1. ARRAYS FOR SINGLE PHOTON DETECTION IN THE NEAR INFRARED

Arrays of photodetectors are increasingly required in many applications,\textsuperscript{1} ranging from x-ray and infrared imaging\textsuperscript{2} to satellite tracking, adaptive optics for astronomy,\textsuperscript{3} wavelength and time-resolved luminescence measurements for biochemistry, just to name a few. Moreover, the availability of solid state laser sources at wavelengths longer than 1\,\mu m is pushing the demand for fast and sensitive photodetectors in this wavelength range, beyond the sensitivity cut-off of silicon devices. For this reason, extensive investigations have been carried out on germanium and III-V APD’s.\textsuperscript{4} Recently we have demonstrated that germanium APD’s cooled at 77K can work in the so-called Geiger-mode, achieving single photon sensitivity with a Noise Equivalent Power (NEP) of $8 \times 10^{-14}$ \,W/\,Hz at 1.3\,\mu m-wavelength and featuring an equivalent bandwidth of 1.8\,GHz.\textsuperscript{5}

A Geiger-mode APD is operated biased above the breakdown voltage, $V_B$. At this bias, as soon as a photon is absorbed in the detector volume, the photogenerated pair triggers a macroscopic avalanche current. A fast discriminator senses the avalanche signal and provides a standard 8\,ns pulse for counting and timing measurements. A variable electronic circuit quantizes the avalanche by lowering the bias close to or below $V_B$ and, after a hold-off time, restores the bias above $V_B$ in order to make possible the detection of another photon. Due to their single photon sensitivity, these devices are also called Single Photon Avalanche Diodes (SPAD’s).

The key feature which makes SPAD’s interesting is that the detector responds to a single photon with a macroscopic current pulse well above the noise level of the following electronics. While sensitivity of analog detectors is impaired by the electronic noise as soon as the signal frequency increases, SPAD’s feature very low NEP not only in measurements of continuous signals but also of very fast optical waveforms. Presently available germanium SPAD’s do not reach the sensitivity of CCD’s or p-n photodiodes in the detection of near-infrared continuous signals, but they become competitive as soon as the signal frequency moves beyond 10\,GHz.\textsuperscript{6} The noise of SPAD’s is due to the so-called dark-counting rate, which is the avalanche rate due carriers generated by thermal activation, tunnelling, or released from trapping centers.\textsuperscript{7} The statistical fluctuations of these events can mask the changes in the photon rate.

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Arrays of SPAD's may combine the sensitivity and the timing performance of the single pixel with the capability of a spatially resolved detection of the photons. Such a device may be employed in wavelength-resolved luminescence, as well as in adaptive optics. This paper reports the first experimental results obtained with a germanium quad-cell operated in Geiger-mode. In Section 2 we describe the detector structure, while the complete characterization of the single pixel is reported in Section 3. A typical problem met in the operation of a Geiger-mode array is the optical crosstalk between pixels. In fact avalanching carriers emit photons by spontaneous radiative recombination or by interaction with phonons. These photons can be absorbed within the sensitive area of a neighbour SPAD, thus triggering it. This illusion is not due to absorption of a signal photon, and it is not a constant contribution like dark-counting rate, since it is correlated to the first triggering of another detector of the array. Therefore the correction of the measured counts for taking into account this effect can be difficult and not accurate. In Section 4 we discuss some methods to face the optical coupling. The simplest one is to sequentially gate the pixels of the cell. We describe the electronics adopted and the performance obtained with this driving method. The conclusion and some perspective are drawn in Section 5.

2. THE GERMANIUM QUAD-CELL

Fig.1 shows the top view of the germanium quad-cell, which consists of four APD's with an active area diameter of 30μm. The centers of opposing pixels are 80μm apart. The sensor was fabricated by EG&G-Judson, Pennsylvania, in a standard germanium technology.

![Top view of the germanium quad-cell](image)

**Fig.1** Top view of the germanium quad-cell.

Fig.2 shows a schematic cross section of the quad-cell, along one of the main axis crossing two of the four APD's. Each active area (p⁺) is surrounded by a guard-ring (p⁻) in order to prevent premature edge breakdown. The channel-stop (n⁻) has been introduced to reduce the surface leakage current. All the APD's share a common cathode, represented by the substrate (n⁻). The substrate is held at a common positive bias while each detector is separately driven through the corresponding anode (see Section 4).

The breakdown voltage $V_B$ of each pixel is 32V at room temperature and decreases to 22.2V at 77K. At a reverse bias of 22V the depleted regions of the four p⁺n junctions touch each and the substrate layer, down to 1.64μm from the top surface, is fully depleted.

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Fig. 2 Cross section of the quad-cell, along one of the main axes. Note the active areas (p⁺) of two SPAD's out of four, the guard-rings (p), and the channel-stops (n⁺). The substrate (n) is the common cathode for all four pixels.

We tested the spatial dependence of the detector sensitivity in the simple experimental set-up shown in Fig. 3. The detector was operated at 300K in the analog multiplying regime biased at 30V, that is below $V_m=32V$. These measurements have also significance for Geiger-mode operation since those carriers contributing to the multiplied analog current, trigger the avalanche pulses in Geiger-mode. The laser was a CW HeNe tube, suitably attenuated and filtered to give a 10μm-spot of 2.2μW. Fig. 4 shows the dependence of the analog current of the East-pixel on the position of the spot along the main axis of the quad-cell. The origin of the reference system is in the center of the quad-cell. The peak photocurrent of 5.8μA corresponds to an avalanche multiplication factor of about five.

Fig. 3 Experimental setup used to measure the analog performance of the quad-cell, mounted on a translating stage. Note that $V_{bias}=V_B$.

Note that the sensitivity of a single pixel (the Eastern one in Fig. 4) is not only confined to its junction area (ranging from 25μm and 55μm on the horizontal axis of Fig. 4). Even when the spot is focused onto the opposite pixel (between -55μm and -25μm) there is a finite probability for holes, photogenerated in the neutral region underneath the depleted zone, to reach by-diffusion the multiplying region of the opposite. The decrease around ±20μm is due to the absorption of photons in the upper neutral region of the p-guard-ring. This extended spatial sensitivity limits the dead-space among pixels: also when the spot is focused in the central region of the quad-cell (between -25μm and +25μm) all four pixels collect photogenerated carriers.
On the other way, carrier diffusion can smear out the differences in the signals of the four detectors, thus decreasing the spatial resolution of the cell. Since the photon absorption length depends on wavelength, the depth of the depleted region must be tailored depending on the spectral range of detector operation.

![Graph](image)

Fig 4: Photocurrent of the East-pixel as a function of the position of a 10μm-laser spot on the major axis of the quad-cell (see inset). The pixel was biased at 94% $V_B$.

### 3. PIXELS PERFORMANCE IN GEIGER-MODE

A good uniformity of the breakdown characteristics of the pixels is of chief importance in SPADs. In fact both the quantum efficiency and the dark-counting rate depend on the excess bias, i.e., the difference between the APD reverse bias above $V_B$ and the $V_B$ value. The operation of an array is easier if all the pixels are at the same voltage. This choice leads to equal excess bias only if their $V_B$ values are very well matched, otherwise the same photon signal causes different counting rates on different pixels. In our samples, we measured an average $V_B$ value of 22.75V at 77K with a maximum difference of 0.5% among the pixels in each quad-cell and of 1% among the pixels of different quad-cells. The average series resistance was 651Ω, with a maximum 12% variation from one chip to the other.

Since in germanium thermal generation is remarkably higher than in silicon, the quad-cell has to be cooled at 77K for being operated in Geiger-mode. At this temperature the main contributions to dark counts do not arise from thermal generation, but from carriers released from trapping centers. By increasing the charge flowing through the APD during each avalanche pulse and/or the avalanche rate, the number of trapped carriers increases. Carriers released when the detector bias is again above $V_B$ contribute to dark counts. This effect is usually referred to as afterpulsing and causes two drawbacks: i) an increase of the dark-counting rate with the excess bias and the avalanche rate (Fig.5); ii) a non-linear relationship between the counting rate of the pixel and the signal intensity.

The simplest way to drive a Geiger-mode APD is the gating operation. A pulse bias periodically raises the voltage of the APD above $V_B$ for short time intervals. If the detector is triggered, a fast discriminator senses the leading edge of the avalanche pulse. The measurements reported in Fig.2 have been performed by setting the gate-on interval to 600ns, leading to an average charge per avalanche pulse ranging from 430pC to 3eC when the excess bias increases from 0.5V to 4V.

The drawbacks of the gated technique are that: i) the detector is enabled only during the gate-on interval, while it is not sensitive for the subsequent off-interval; ii) the avalanche current flows until the end of the gate-on interval, therefore the number of trapped carriers increases as the gate-on interval increases, thus enhancing the afterpulses. However, due to its simple implementation, we have performed the first tests of the quad-cell in gated-mode operation. The design of quenching circuits for optimizing the detector driving will be the task of future efforts. In the meanwhile, afterpulsing reduction has been
pursued by adopting a short gate-on time interval and by biasing the APD 0.2V below $V_B$ between two subsequent gating pulses. In this way, the presence of a high electric field in the junctions, even when the detector is held off, helps the release of the trapped charge, via the Franz-Keldish effect. The details of the gated operation of the quad-cell will be given in Section 4.

![Graph showing dark-counting rate vs excess bias for 1kHz and 10kHz frequencies.](image)

**Fig.5** Dark-counting rate of a pixel at 77K versus excess bias at a gating frequency of 1kHz and 10kHz. The gate-on intervals lasted 600ns, while during the gate-off intervals the detector bias was 0.2V below $V_B$.

Timing performance is not important for quad-cell detectors which are usually employed for detecting the centroid of the impinging optical signal. Instead, it is a key feature for linear arrays which may be developed for making possible wavelength and timing-resolved luminescence in the near-infrared. We have already demonstrated that single germanium APD’s can measure the arrival time of single photons with a resolution better than 100ps Full Width at Half Maximum (FWHM). Thinking to future design of linear arrays of SPAD’s, we have tested the temporal response of the pixels of our quad-cell. The measurements were performed in a conventional time-correlated single photon counting setup. Fig.6 shows the typical response of a pixel to a 60ps-laser pulse at 1.5um, when the quad-cell is biased at 2V above $V_B$. By quadratically subtracting the laser width from the experimental FWHM, the intrinsic time resolution of the detector is estimated to be 113ps FWHM. The slow tail in the response is due to carriers photogenerated in the neutral regions reaching the pixel junction by diffusion. The best time resolution of 98ps FWHM has been obtained at 3V above $V_B$.

![Graph showing timing response of a pixel at 77K and 2V above $V_B$.](image)

**Fig.6** Timing response of one pixel of the quad-cell at 77K and 2V above breakdown. The width of the 1300nm laser pulse was 60ps.
4. PHOTON COUNTING WITH THE QUAD-CELL

The first problem met when an array detector is operated in Geiger-mode, is the optical crosstalk between pixels. This is due to secondary photons emitted by avalanching carriers. In order to quantitatively assess this effect, we measured the dark count rate of one pixel, the "detector", as a function of the continuous reverse current flowing through another pixel of the cell which acts as emitter of secondary photons. The detecting pixel was operated in Geiger-mode at an excess bias of 0.5 V. Fig. 7 reports the experimental results. Like in silicon devices, the count rate linearly increases with the current of the emitting pixel. The slope of the straight line at 77K corresponds to $2.8 \times 10^{10}$ secondary photons detected per carrier crossing the emitting APD. Fig. 7 also shows the results of counting measurements at 20K. Even if the emission efficiency of secondary photons is very low, the intense current flowing during the SPAD avalanche pulse makes optical coupling very strong. In conventional analog detection, with APD's biased below $V_B$, the avalanche current is instead order of magnitudes lower and crosstalk due to secondary photon emission is negligible.

![Graph showing optical crosstalk among the APD's of the array. The avalanche current imposed in the "emitting" pixel leads to a correlated counting in the "detecting" pixel.](image)

A way to overcome photon cross-talk among pixels is to operate the array with an anti-coincidence circuitry, which counts only the first event, while discarding all the others following within a controlled coincidence-interval. Since in the anti-coincidence time interval the pixels can be triggered only by secondary photons and dark counts, but also by signal photons, the anti-coincidence time interval must be no longer than few tens of nanoseconds, in order not to impair the detector sensitivity. This constraint requires the design of fast electronics and it brings many problems for both circuit layout, data acquisition and processing. Therefore, in this first demonstration of the quad-cell operation we decided to avoid optical crosstalk by adopting another driving procedure: a multiplexed gating of the pixels.

Fig 8 schematically shows the bias and the timing of the gating controls. Each pixel is sequentially enabled for a gate-on time interval $T_{on}$ and the array is scanned sequentially with a period $T_g$. The four pixels have been named North, East, South and West. In our experiments, the quad-cell was biased at 77K, reverse biased at 22V, that is 0.2 V below $V_B$ and the amplitude of the gating pulses was $0.7 \text{V}$. Each pixel is enabled to detect signal photons only when the negative gating pulse $-\Delta V$ is applied to its anode and its overall bias is raised 0.5 V above $V_B$. Note that the pixel can be triggered only once within the corresponding gate-on time interval and the avalanche current lasts until the end of the gating pulse. Therefore if $\Delta V_{threshold}$ is the dark count rate and $n_e$ is the expected photon rate, the maximum sensitivity of the apparatus is reached for $T_{on}=\frac{\Delta V_{threshold}}{n_e}$. It can be shown that in all cases where $n_e<\Delta V_{threshold}$, the adoption of a multiplexed gating causes only an increment for a factor of four of the measurement time required to reach a unit signal to noise ratio. Our measurements were performed with $T_{on}=500 \text{ns}$ and $T_g=2 \mu s$.

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Fig. 8  Multiplexed gate mode of the quad-cell. In this way the optical crosstalk is avoided.

Fig. 9 shows the block diagram of the experimental setup. The ECL main clock and the shift register provide the synchronisation signals for the drivers, which deliver the negative gating pulses $\Delta V$. The common base transistor biases the quad-cell at a reverse voltage of 22V, picks up the avalanche current and feeds it to the discriminator. As a pixel is triggered, the discriminator output pulse is counted by the corresponding counter. In our measurement we subtracted the counts of opposite pixels (North-South and West-East) to measure the spatial offset of the laser spot onto the quad-cell. In the following, we will show the results we obtained when we used the cell signals to drive an XY-translating stage, in order to adjust the position of the laser spot in the middle of the quad-cell.

Fig. 9  Photon counting experimental setup to monitor the photon absorption position within the quad-cell.
Figs. 10 and 11 show the counts of the West and East SPAD’s when a 10μm-laser spot at 1μm-wavelength is moved along two directions. The average power at the spot was 0.76mW, corresponding to 2256 photons impinging on the quad-cell in the 500ns of T_{on}. The sampling frequency was 1/T_{s} = 500kHz and for each position of the spot the counts were collected for T_{on}=10s.

**Fig. 10** Counts of the West and East pixels, when a 10μm-laser spot is moved along the West-East axis.

**Fig. 11** Counts of the West and East pixels, when a 10μm-laser spot is moved along the SW-NE diagonal of the quad-cell. The direction of scan is intentionally closer to the West pixel.

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In order to test the tracking capabilities of the quad-cell, we used it in a very simple feedback loop. The difference between the counts of opposite pixels have been used to move the laser spot with a micropositioning stage (Microcontrolor ITDCA2) controlled via software. The operating conditions were the same of the measurements reported above, except for the integration time which has been set to $T_m = 4$sec. At each control iteration the spot was moved by a constant step of 1μm. Fig. 12 shows the position of the laser spot in the reference system of the micropositioning stage, with the origin in the cell centre.

![Fig.12 Tracking: vertical and horizontal displacement by the cell centre plotted for successive step of the simple control system described in the text.](image)

At the beginning the centroid of the laser spot was 11μm far from the center. It takes 40sec to reach the center with a spatial accuracy of ±1.5μm. This is just a demonstration of the tracking capability of the detector. Better control strategies can be implemented to achieve a faster response and a better spatial resolution.

5. CONCLUSION AND PERSPECTIVE

We have investigated for the first time the performance of a fully integrated germanium quad-cell operated in Geiger-mode. Such type of detector are promising for the adaptive optics system and tracking applications in the near infrared. We have demonstrated that the detector pixels can be easily operated with multiplexed gating bias pulses, thus avoiding the optical cross-talk due to secondary photon emission. Moreover a simple tracking test has been implemented and successfully performed. Regarding the cell sensitivity there is a lot of room for future improvements. Since the limit due to optical cross-talk has been overcome, the dead space between pixels can be further reduced without impairing the detector performance. Moreover technological improvements are expected to reduce the afterpulsing effects which is responsible for the high dark count rate. The detector is also suitable for time and wavelength resolved luminescence, where it is possible to fully exploit the 100ps timing resolution of each pixel in the near-infrared.

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REFERENCES


