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Abstract:

Some decades ago single photon detection used to be the terrain of photomultiplier tube (PMT), thanks to its characteristics of sensitivity and speed. However, PMT has several disadvantages such as low quantum efficiency, overall dimensions, and cost, making them unsuitable for compact design of integratedsystems. So, the past decade has seen a dramatic increase in interest in new integrated single-photon detectors called Single-Photon Avalanche Diodes (SPAD) or Geiger-mode APD. SPAD detectors fabricated in a standard CMOS technology feature bothsingle-photon sensitivity, and excellent timing resolution, while guarantying a high integration. SPAD are working in avalanche mode above the breakdown level. When an incident photon is captured, a very fast avalanche is triggered, generating an easily detectable current pulse.

In this work, we investigate the design of SPAD detectors using the austriamicrosystems' 0.35 µm CMOS Optotechnology. A series of different SPADs has been fabricated and benchmarked in order to evaluate a future integration into a SPAD-based image sensor. The main characteristics of each SPAD operating in Geiger-mode are reported: current voltage, breakdown voltage as a function of temperature. From this first set of results, a detailed study of the Dark Count Rate (DCR) has been conducted.

Our results show a dark count rate increase with the size of the photodiodes and the temperature (at T=22.5°C, the DCR of a 10µm-photodiode is 2020count.s-1 while it is 270 count.s-1 at T=-40°C for a overvoltage of 800mV).

We found that the adjustment of overvoltage is very sensitive and depends on the temperature. The temperature will be adjusted for the subsequent experiments.A mathematical model is presented for reproduce the DCR of a single photodiode. We simulated the noise (DCR) of array of 32x32 photo-detectors.Our results show, of course an increase of DCR of 1024, but especially, the probability of having two pulses simultaneously is 0 (without light). By studying these probabilities of occurrence of the pulses, we think we can reduce the DCR of 50% with a statistical method and reduce the crosstalk of 90%.This study is realized in order to prepare the first digital matrices sensor in Geiger mode.

1 Introduction

The Geiger-mode APD is a new semiconductor photon sensor, which has a high photon countingcapability.The system is described in detail in [Ref 1]. The Silicon Photomultiplier (SiPM) is a multi-cell silicon photodiode (typical cell size isfrom D= 10 to 50µm) joined together on a common substrate and working on a common load. The silicon avalanche microcells with very low noise current are operated in the Geiger mode, in which the bias voltage is above the diode breakdown voltage (typicalVbr=10 to 100V).The typical density of microcells is 400–5000 per mm^2. The first developmentstarted about 10 years ago in Russia [Ref 2]. Hamamatsu Photonics produces the Multi-Pixel Photon Counter MPPC since 2008.It is a type of SiPM.The SiPM is described in details in [Ref 3].Currently, several technologies have been developed. Good performances have been measured.A good performance comparison is described in details in[Ref 4][Ref 5]. We introduce in this paperour researchin the Geiger mode with the technology "CMOS-Opto C35B4O1" proposed by CMP (Circuit Multi-Projects) in Grenoble and manufactured by AMS (Austria Micro-system).These sensors, and this operating mode, have a significant defect: a lot of noise.We propose in this paper a DCR study with new measures in order to lessen the noisewith new measurements in order to lessen the noise.

2 The Technology "CMOS-Opto C35B4O1", and breakdown voltage simulation

This "CMOS-Opto C35B4O1" process is made with a Pepi-layer (thickness ≈14µm) on a P type substrate.This 0.35 CMOS-Opto process offers 4 metallization layers and 2 polysiliconlayers.Figure 1shows the cross-section.The saturation current for NMOS is 520µA/µm and 240µA/µm for PMOS, which is ideal for the transistor quenching. P-epi wafers allow lower current leakage in the diode, then a lower dark current for a better sensitivity. The Dark current < $45pA/cm^2$ is very low, which is ideal for the Geiger mode. This technology is sensitive in the range 400-1000 nm.There are 3 p-type layers of different doping levels to suitably modify the field distribution across the structure.The first one is a thin p^+type layer used for a good contact of the photodiode anode(doped Boron 1.10^{20}atom.cm^{-3}).The second one is a p^-epi-layer (doped Boron 1.10^{17}atom.cm^{-3}). The third layer is a heavily doped p^+layer (substratedoped Boron 3.10^{18}atom.cm^{-3}). There are 2 n^-typelayers of different doping levels.The first one is a thin n^+type layervery sensitive to the light(doped Phosphorus 1.10^{19}atom.cm^{-3}). The second n^-layer is theguard ring (doped Boron 1.10^{17}atom.cm^{-3}).These doping values were found by SIMS and the profiles will be published soon. We expose the results obtained in simulation with these doping values. The Figure 2 presents a first simulation of the structurewith the 4 zones and the doping correctly adjusted. The software "Silvaco" was used for these simulations. The result of these simulations at 22.5°C(Figure 3) gives us a breakdown voltage of 11.7V and a guard ring of 40V.At this point of our work, we can say that this technology is well suited to Geiger Mode.

3 Experimental results: Breakdown voltage

We present here the experimental results obtained for several photodiodesof different diameter. These are isolated photodiodes. The diameter of the photodiodes is between D=200μm and D=2.7μm (200,100,50,20,10,7,6,5,4,3 and 2.7)μm. The size of the guard ring is 1.7μm. The structural dimension is shown in Figure 4.The breakdown voltage values have been determined from the reverse current–voltage (I–V) characteristics, using aKeithley2636A. A breakdown voltage of 11.7V was measured at 22.5°C for photodiodes with a diameter greater than or equals to 10μm. For photodiodes with a diameter lower than 10μm diameter we measured a higher breakdown voltage (near of guard ring 40V) (Figure 5). Measurements have been repeated on a significant number of devices, showing a very good uniformity of the breakdown voltage values and confirming the reliability of the technology used for the Geiger mode.We measured on Figure 6 the temperature sensitivity for breakdown voltage: 9mV.°C^{-1}. It is found that the temperature has a strong influence on breakdown voltage and therefore on the overvoltage.

4 Experimental results: Dark count rate

This is a first positive result concerning the dark count rate (DCR)using only one isolated photodiode. The behavior of the quenchingsystem is correct.At 22.5°C the dark count rate, for a photodiode of D=10μmdiameter, and an 800mV overvoltage, is 2020count.s^{-1} (Figure 7).At -40°C the dark count rate, for a photodiode of

D=10µmdiameter, and an 800mV overvoltage, is 270 count.s^{-1}(Figure 8).These two results are presented in Figure 9. The Figure 10, resume all these results. With a diameter lower than 10µm, the DCR does not diminish anymore which confirms that the smallest diameter for this technology isabout D=10µm.The Geiger pulses were measured with a universal counter "Hameg HM 8021-4".These values are comparable to those reported in literature for CMOS SPADs built in a similar technology: AustriaMicroSystems technology 0.35µm high-voltage:[Ref 6].

5 Experimental results: The noise distribution (DCR distribution) and Simulation results

These results are new. We measured the time between each pulse. We presenton the Figure 11 the DCR distribution. We used a small photodiode: dimension D=10 µm. With these results we can calculate the probability occurrence of one pulse as shown Figure 12. The Figure 12allows us to build a photodiode model with experimental values of DCR.We simulate Figure 13 an array of photodiodes 1024 and we can calculate the probability of double or triple pulse.

6 Conclusion

We introducedin the present document an investigation of thetechnology "CMOS-Opto C35B4O1" proposed by CMP (Circuit Multi-Projects) in Grenoble and manufactured by AMS (Austria Micro-system) for the Geiger mode.The main part of our work dealt with the Characteristics in the dark and allowed to find the size of the photodiode with the smallest DCR.The first results that we have obtained are in good agreement with the challenge of the Geiger mode.Other results will be reported in a forthcoming paper.

Uneoudeux phrases sur la dispersion du bruit

7 References

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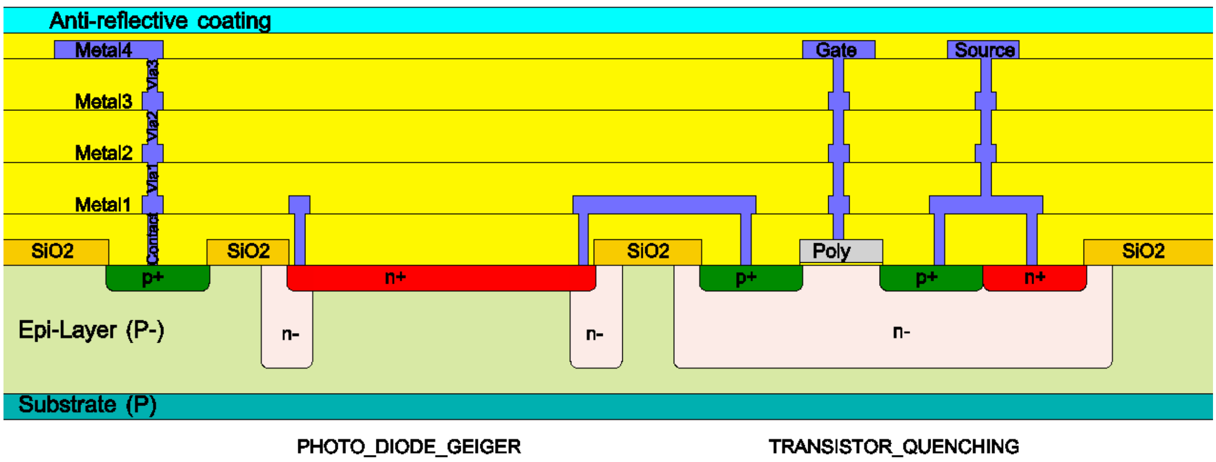

Figure 1: Cross-section of the Photodiodes design (SPAD)for Geiger mode in CMOS-Opto C35B4O1

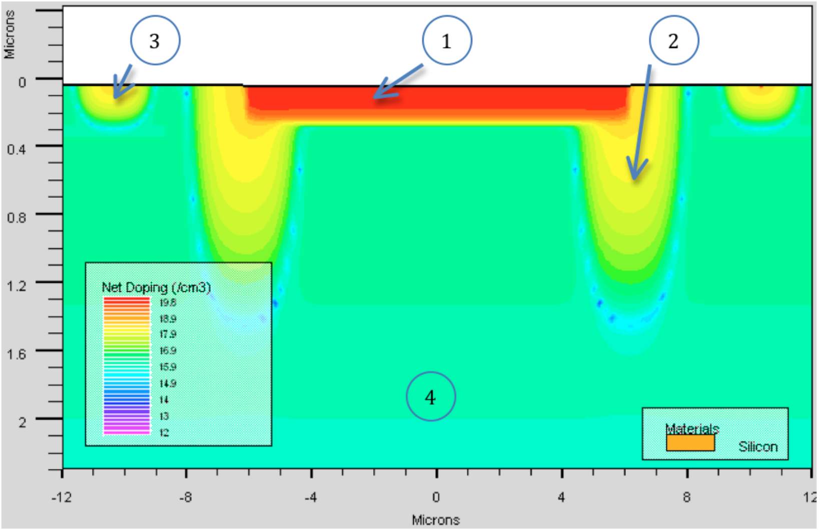

Figure 2: Cross-section, simulation "Silvaco" of the structure: N⁺/P junction and guard ring N⁻ layer.

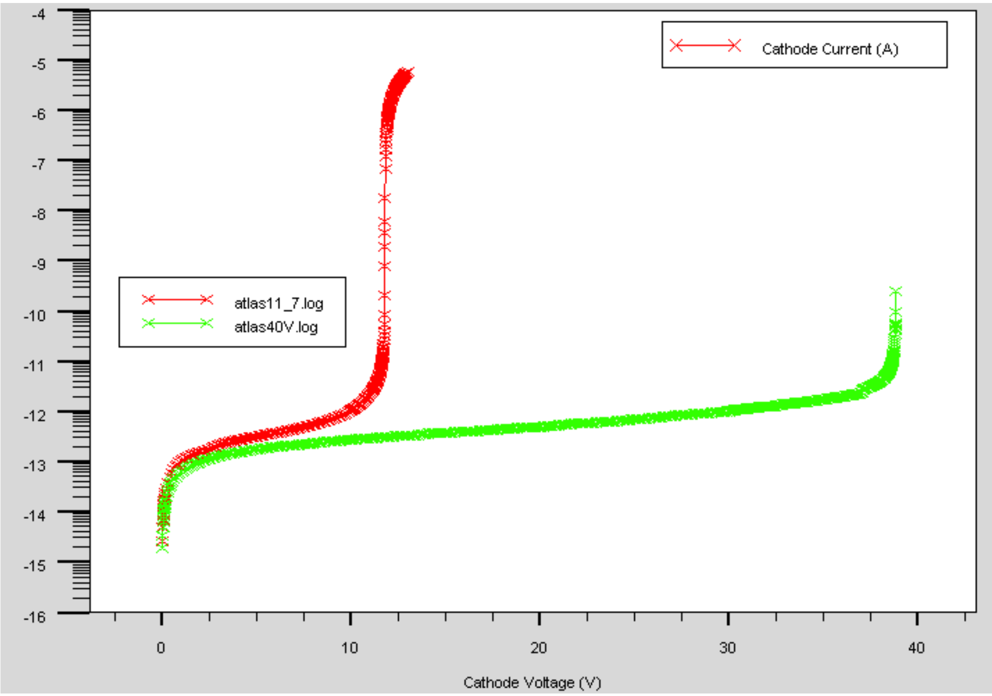

Figure 3: breakdown voltage of the photodiode and breakdown voltage of the guard ring; simulation results obtained at 22.5°C

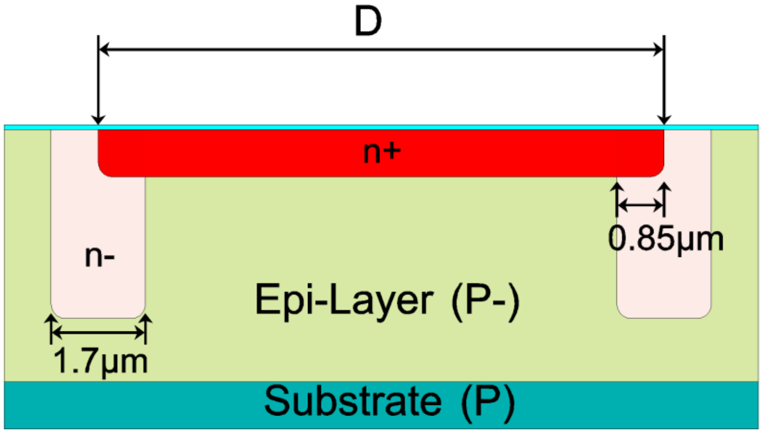

Figure 4: Schematic structure: Size of guard rings and size of photodiodes

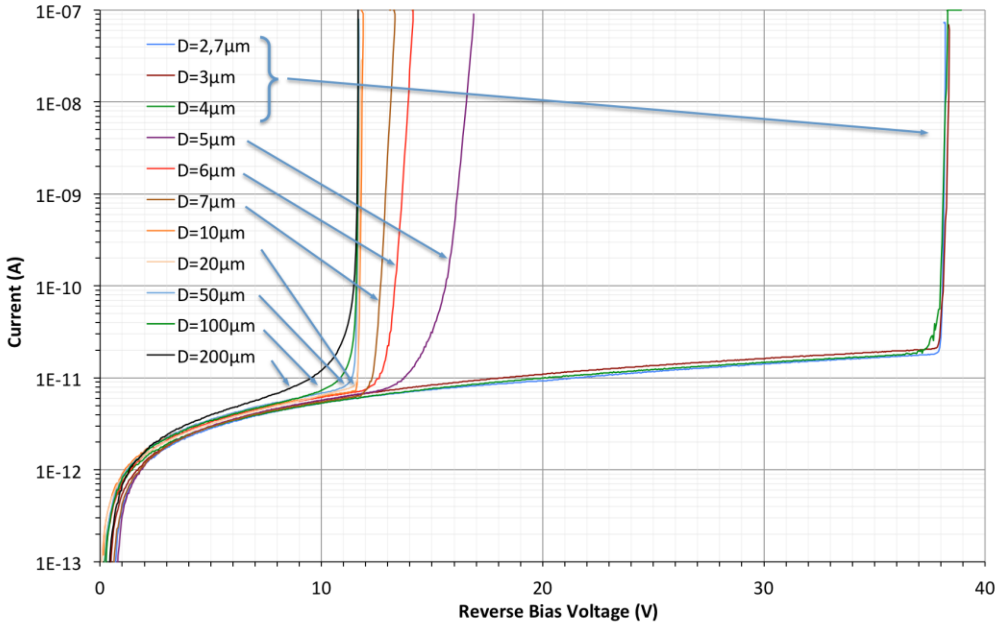

Figure 5: Breakdown voltage of the photodiodes; experimental results obtained at 25°C

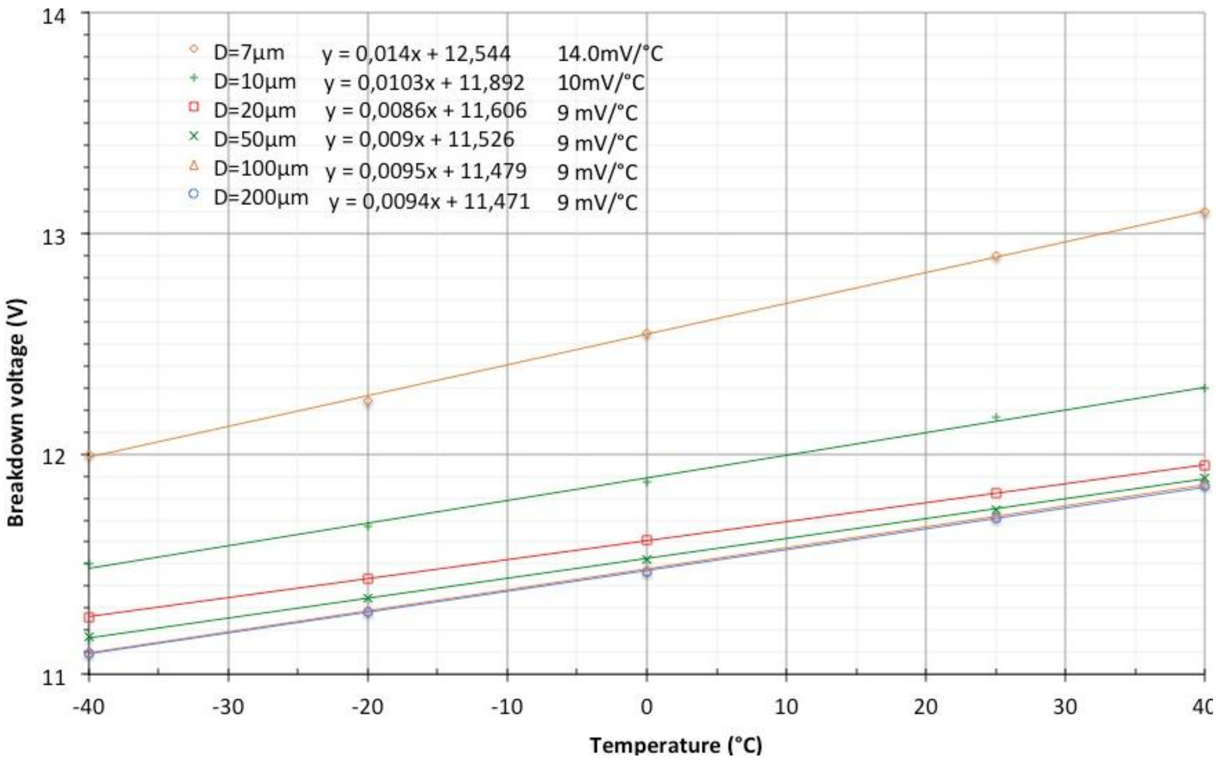

Figure 6: Breakdown voltage versus temperature for different size

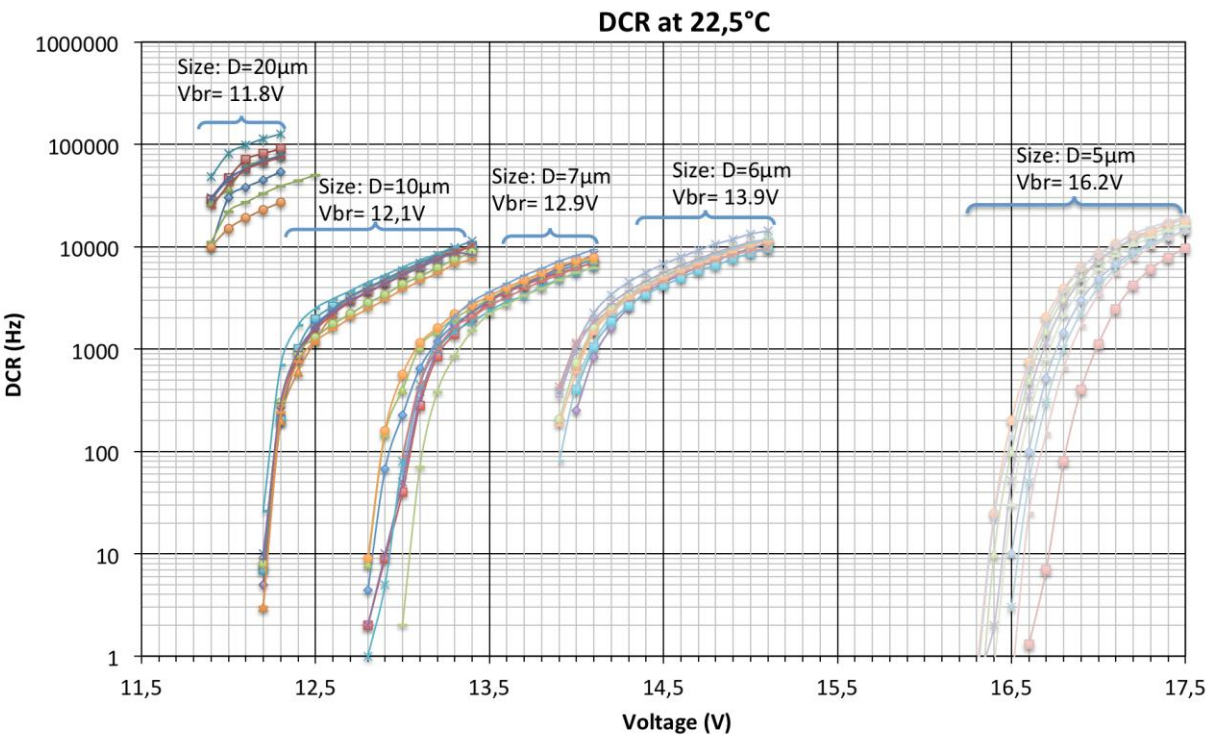

Figure 7: Dark count rate versus photodiode voltage at 22.5°C.

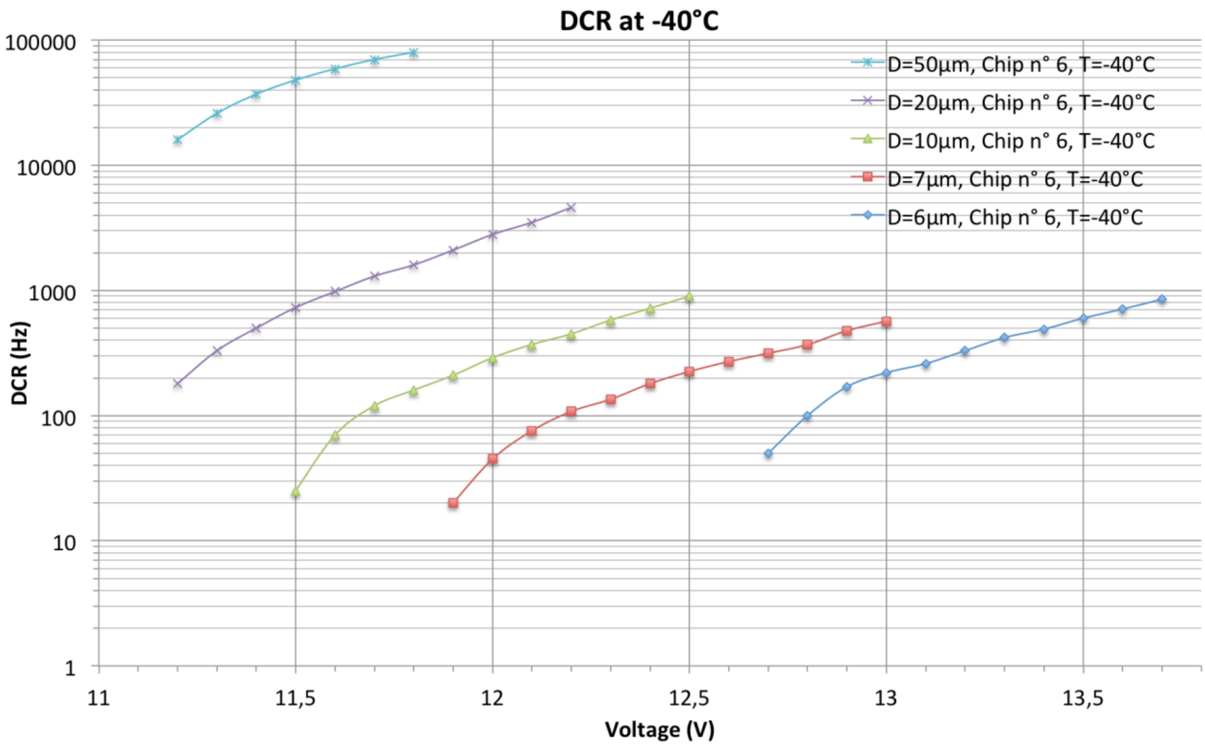

Figure 8: Dark count rate versus photodiode voltage at -40°C

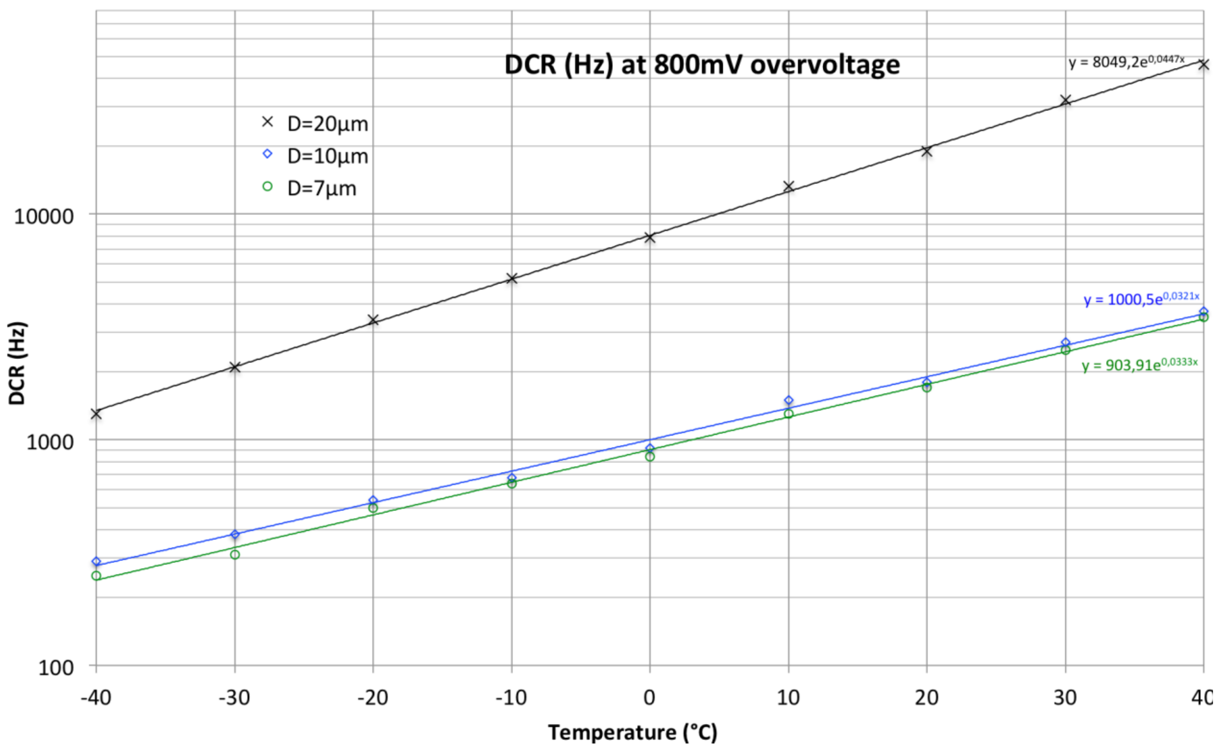

Figure 9: Dark count rate versus Temperature for three size at 800mV overvoltage

D (µm)	22.5°C		−40.0°C	
	Vbr (V)	DCR at 800mV overvoltage (Count/s)	Vbr (V)	DCR at 800mV overvoltage (Count/s)
200	11.70	overflow	11.15	overflow
100	11.70	overflow	11.15	overflow
50	11.70	65000	11.15	45000
20	11.80	21000	11.18	1200
10	12.10	2020	11.49	270
7	12.90	1900	11.80	260
6	13.90	1900	12.40	260
5	16.20	1900	15.60	260

Figure 10: summary table of our design

Figure 11: The nose distribution

Figure 12 :probability of occurrence over time

Figure 13 : Simulation DCR of a photodiode array