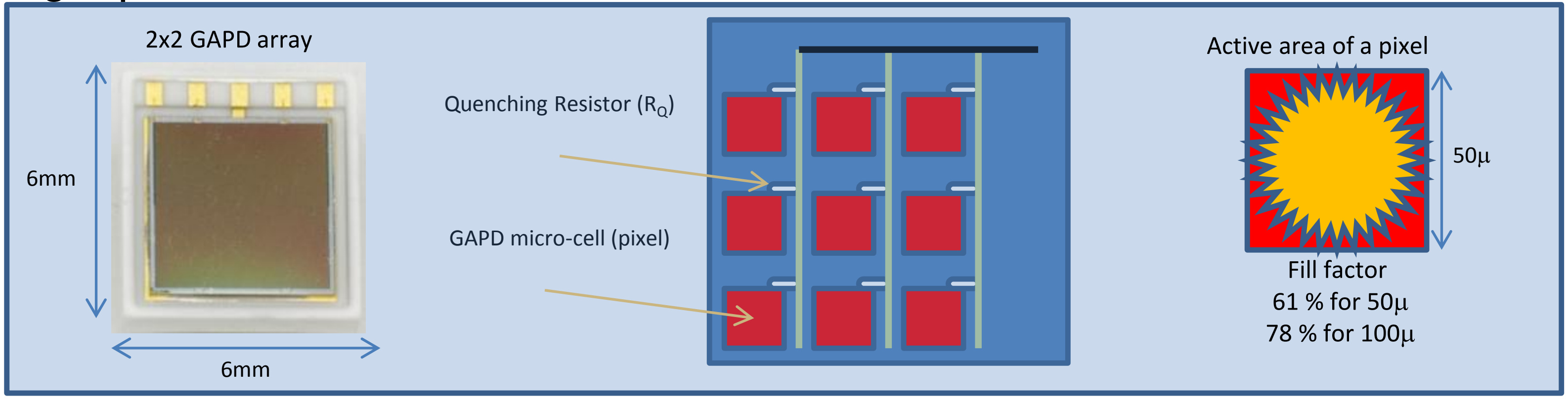
GAPD : Characterisation for Imaging Atmospheric Cherenkov Telescope

GAPD: Geiger Avalanche Photo Diode (SiPM, MPPC)

The Geiger-mode avalanche photodiodes (GAPDs) are array of silicon photo diodes (SiPM). A GAPD turns on in saturation stage as photon falls on when biased above the breakdown voltage ($V_{bias} > V_{bd}$) and allow the detection of single photon.



GAPDs are made by doping Silicon wafers to create a pn-junction type of diode. A lightly doped silicon favours for avalanche mechanism. GAPDs are composed of individual electrically and optically isolated pixels. Each pixel (or microcell) has its own quenching resistor to stop the discharge. The signals from all the microcells are summed to give a signal proportional to the number of microcells triggered.

$$\sum \textit{digital}\ \text{signals} = \text{analog signal}$$

Working Principle:

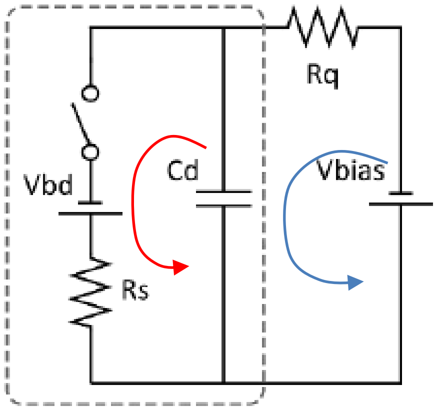
Avalanche take place in n^+/p region when $V_{bias} > V_{br}$

In a microcell, p/n junction can be modelled as C_D in series with the quenching resistance R_Q.

(C_D : geometry of microcell : 50 to 500 fm farad)

Photon initiate an avalanche by impact ionization. This state can be modelled as a voltage source V_{bd} with series resistance R_s

The equivalent circuit of GAPD



When avalanche is triggered : C_D start discharging through R_s with time constant

$\tau_D = C_D \times R_s$ ($500 \times 10^{-15} \times 100 = 50$ps)

The current through quenching resistor (I_{max})

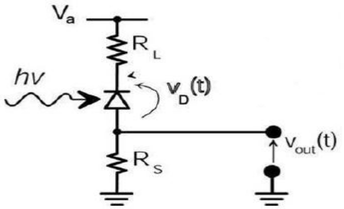
The voltage drop across R_Q reduces diode voltage below the V_{bd} and quenching the avalanche.

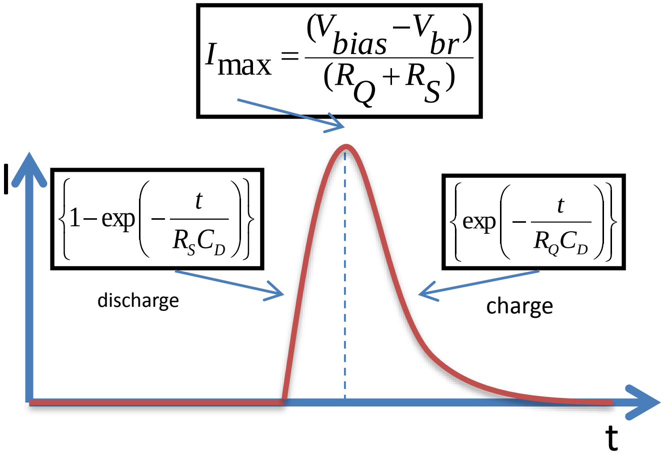
The charging of C_D starts with time constant

$\tau_Q = C_D \times R_Q$ give the slow exponential decay of the GAPD current/signal and determine the recovery time (20ns to 300ns) of the microcell.

The GAPD gain $G = \frac{Q(\text{single avalanche})}{q_e} = \frac{I_{max} * \tau_Q}{q_e} = \frac{C_D * (V_{bias} - V_{br})}{q_e}$

Simple biasing circuit of GAPD





$$I_{max} = \frac{(V_{bias} - V_{br})}{(R_Q + R_S)}$$

$$\left\{1 - \exp\left(-\frac{t}{R_S C_D}\right)\right\}$$

discharge

$$\left\{\exp\left(-\frac{t}{R_Q C_D}\right)\right\}$$

charge

GAPD：Physical & Electrical parameters

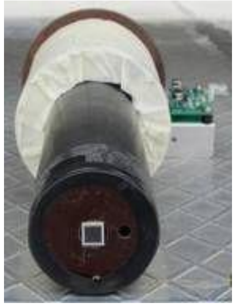
HAMAMATSU

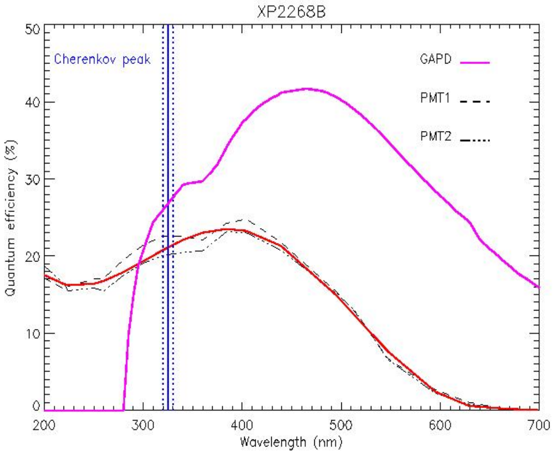
GAPD/ MPPC/SiPM	**S12572-050C**
Effective photo sensitive area	3x3 mm
Pixel pitch	50 µm
Fill factor	61 %
Number of pixels	3600
Operating voltage	V_{bd} (at 25 ºC) + 5V
Terminal capacitance	320pf
Operating temperature	0 to 40 ºC
Storage temperature	-20 to 60ºC
Spectral response	320-900 nm
Peak sensitive wavelength (λ_p)	440 nm
Temperature coefficient	56mV ºC
Amplifier gain (from evaluation kit)	20

$$\eta_{Si} = 80-90\%$$

$$\eta_{PMT} = 30\text{-}35\,\%$$

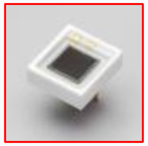
$$PDE = \eta * fil * P(A)$$





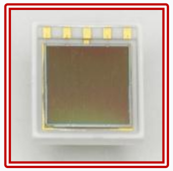
GAPD Size Selection:

$3^{mm}x3^{mm}$



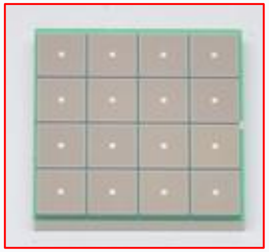
Single ch

$3^{mm}x3^{mm}$



2x2 array

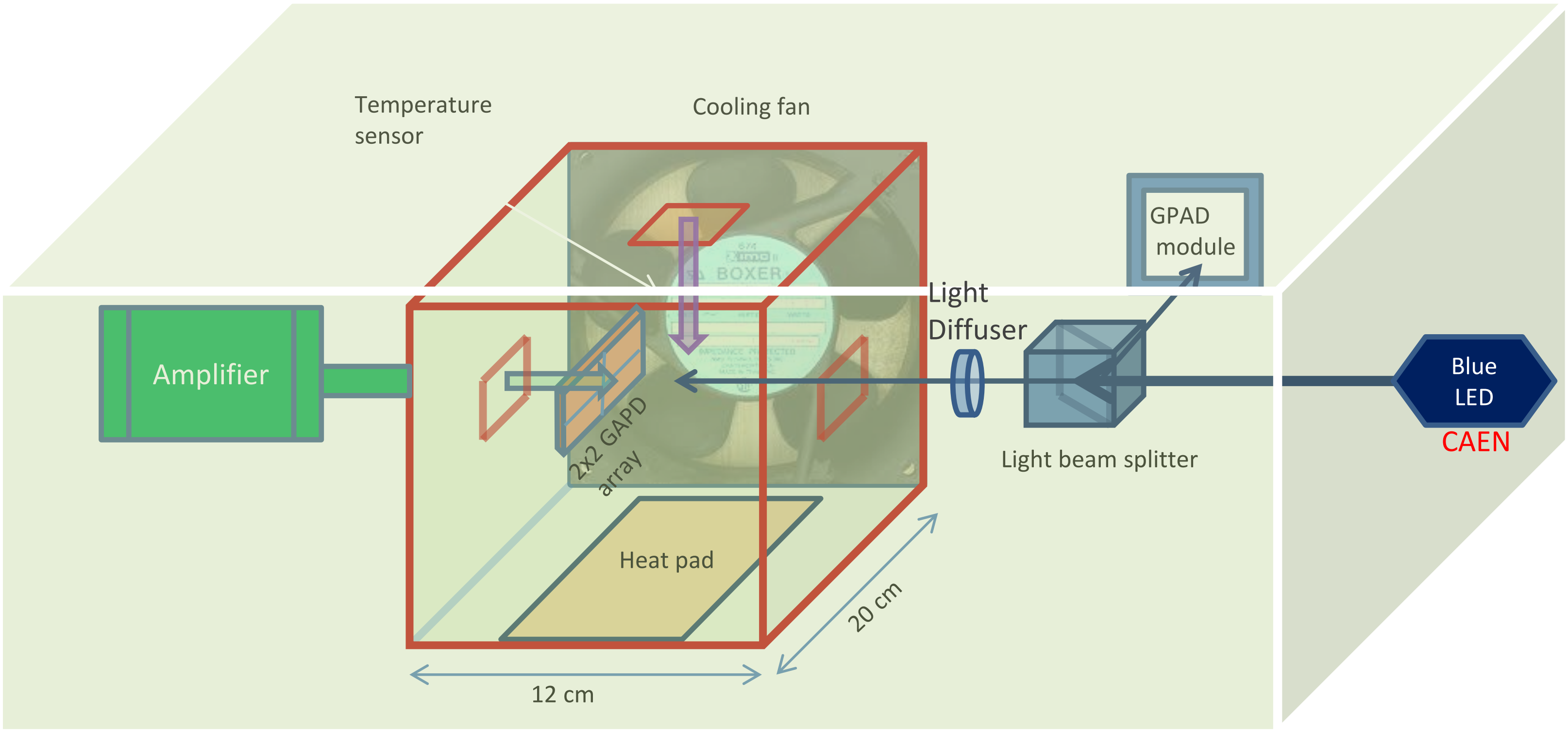
$3^{mm}x3^{mm}$



4x4 array

TACTIC Telescope: spot size 20 mm diameter

Experimental Setup



Measurements :

[1] Standard GAPD module (stability of light source)

[2] Break down voltage/operating over-voltage

[3] Dark counts (thermal + after-pulsing)

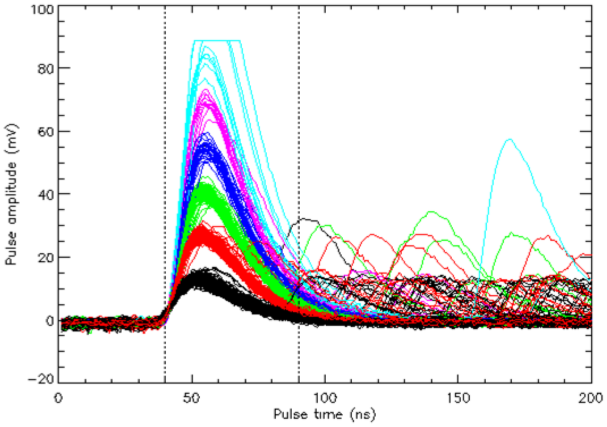
[4] Temperature dependence of Breakdown voltage

[5] Measurement of absolute gain and its linearity

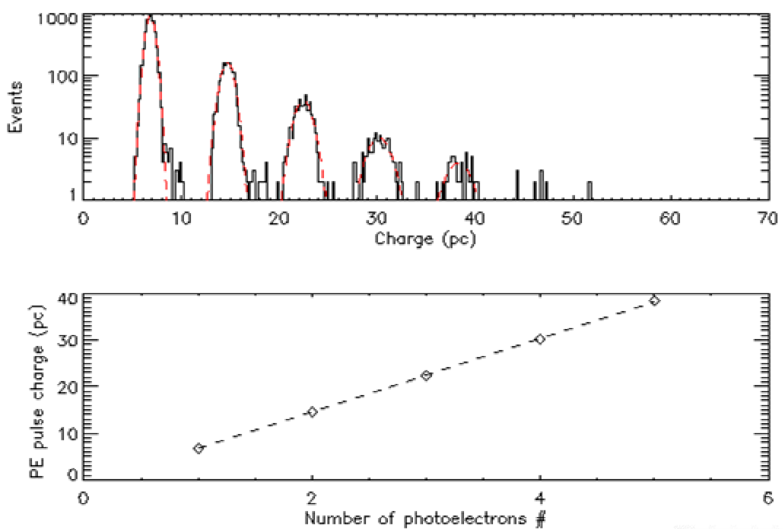
[6] Gain Temperature dependence

[7] PDE measurement

GAPD module (Hamamatsu)



Dark pulse profiles



C11205 GAPD module

Peak # (PE)	Amplitude (mV)		Charge (pc)	
	Peak position	Width	Peak position	Width
1	12.96	1.56	6.79	1.00
2	26.53	2.08	14.66	1.41
3	40.68	3.40	22.45	1.87
4	54.41	3.88	30.17	2.51
5	68.58	5.37	38.30	2.83

Pulse amplitude and charge increases linearly with number of photoelectrons produced.

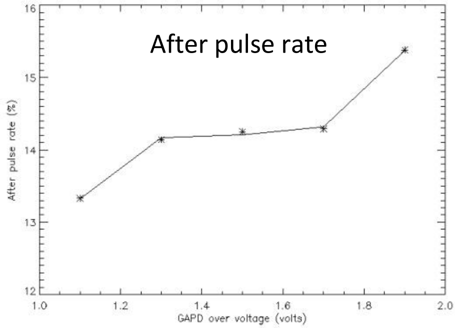
$Q/e = 7.85$ pc

$R = 50\ \Omega$

$g_a = 20$ (amplifier gain)

$(1e) * g_a * G = Q$

$\mathrm{Gain}_{GAPD} = 2.45\times10^6$

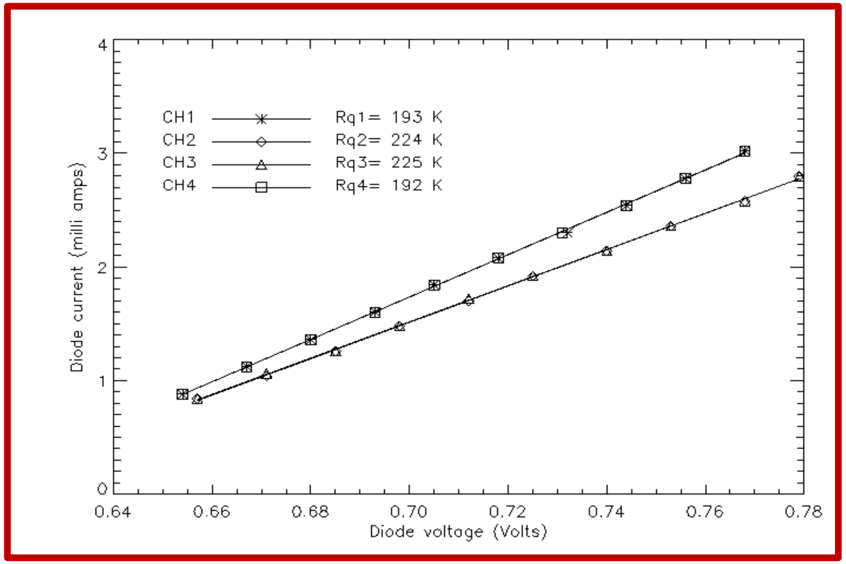


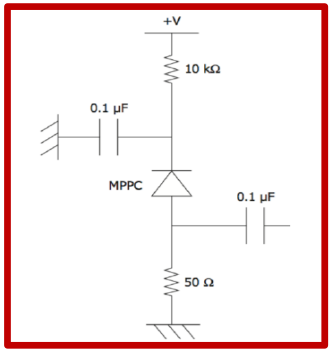
Peak width α number of fired pixels.

$$G = \frac{C\,\Delta V}{q}$$

Pixel capacitance can be used as a measure of pixel uniformity.

Quenching Resistor : Micro-cells in GAPD are connected in parallel through a decoupling resistor, which is also used for quenching avalanches in the cells.



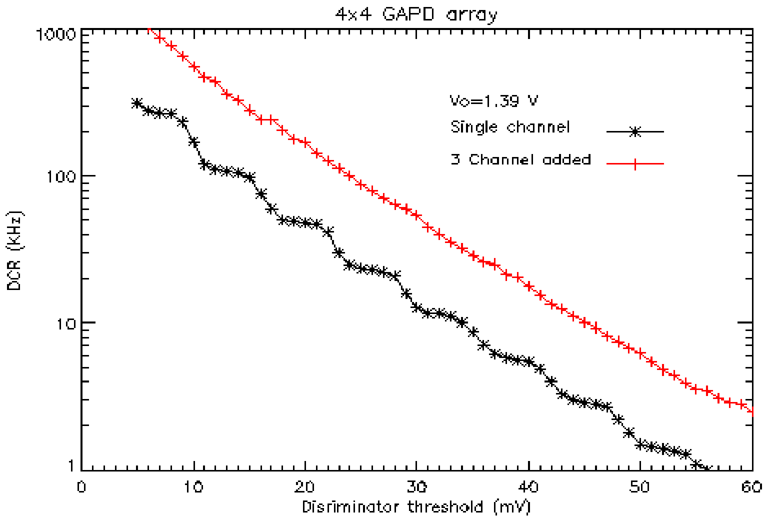


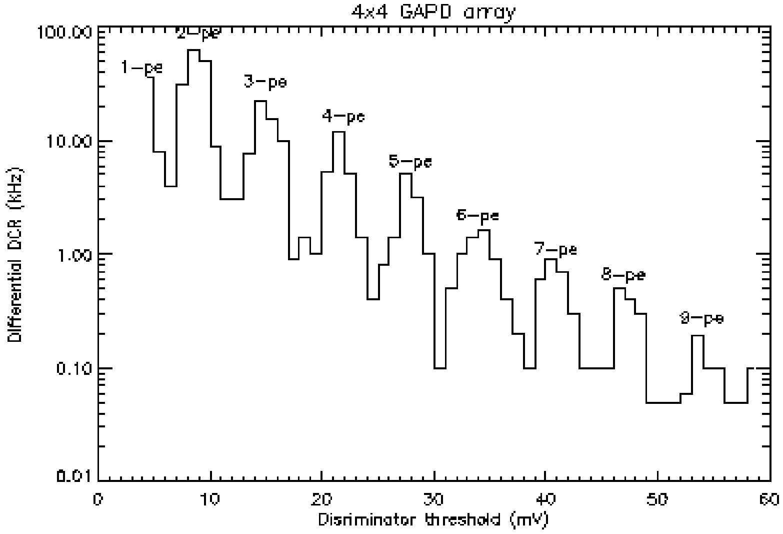
$$R_Q = 3600\frac{dV}{dI}$$

Measurement method : Forward biased GAPD

Dark count rate (DCR)

The DCR of a GAPD is the pulse count for > 0.5 photo-electron level





Primary dark noise : Primary dark noise pulses are due to thermally generated carriers in the µcell of p+ /n junction. Count rate increases with the Temperature (T) at given gain.

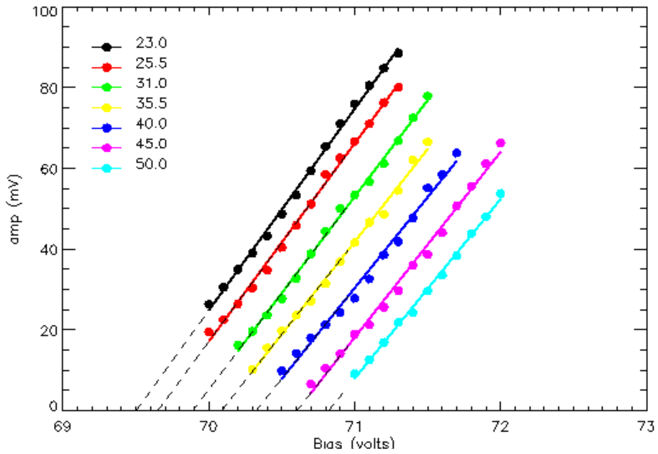
$$n_i \,\alpha\, \mathrm{N_D} T^{3/2} e^{-Eg/2kT}$$

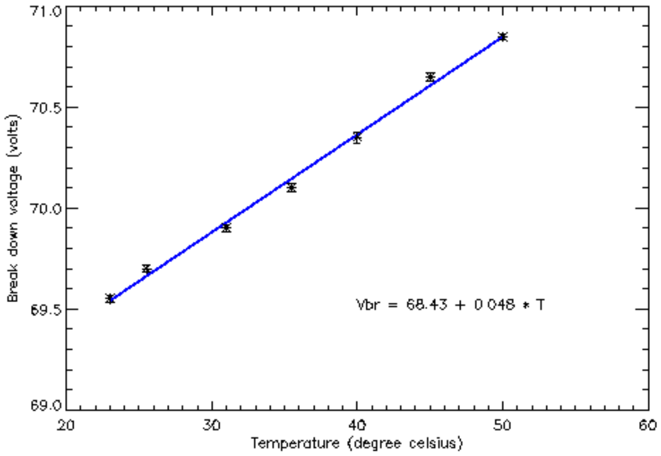
This rate also increases with ΔV because of increase in the avalanche triggering probability.

Secondary dark noise : Pulses are due to after-pulsing and cross-talk effects and they may account for a large fraction of the total DCR. Trapped charge carriers during the avalanche mechanism released later can trigger a subsequent avalanche, generating after pulses correlated with a previous avalanche pulse.

The traps lifetime depends on temperature (T, ΔV). Emission of hot-carrier induced (recombination process) photons in avalanching can trigger avalanches in adjacent µcells generating simultaneously signals with the primary ones (optical cross-talk).

Breakdown voltage : The bias voltage at which the Geiger breakdown occurs in GAPD is called the *breakdown voltage* (V_{bd}). The breakdown voltage shows strong temperature dependence.





$$V_{bd}\ \text{(volts)} = 68.43 + 0.048 * \mathrm{T}$$

The effect of an increase in temperature in semiconductors,

(a) The mobility ($v_d = \mu E$) decreases

(b) Carrier concentration (e/h) increases exponentially.

$$n_i \ \alpha \ \mathrm{N_D} T^{3/2} e^{-Eg/2kT}$$

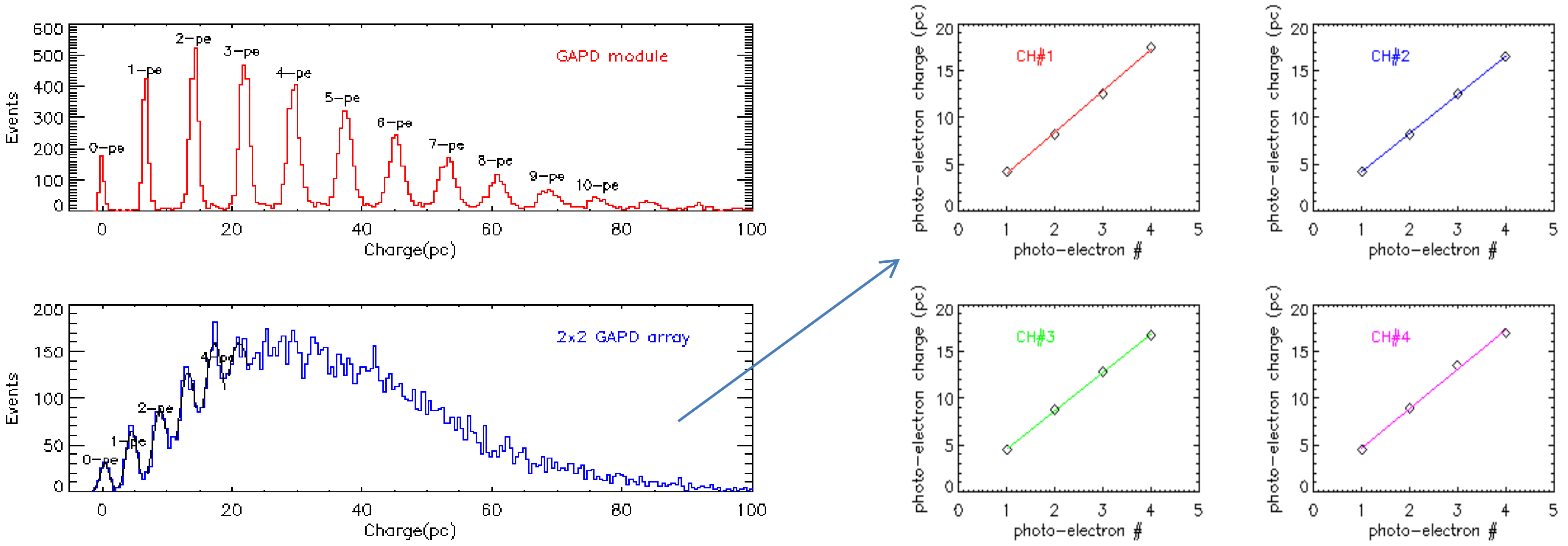
Resistivity of semiconductor decreases with increase of temperature. (negative temperature coefficient)

Avalanche break down occurs in lightly doped pn-junctions where depletion region is comparatively long. The doping density controls the breakdown voltage. In case of GAPD increase in carrier concentration does not compensate for loss of mobility so resistivity increases (positive temperature coefficient)

In GAPDs, Increase of temperature increases the breakdown voltage.

Input parameter for bias control circuit

Photo-electron spectrum：Absolute gain

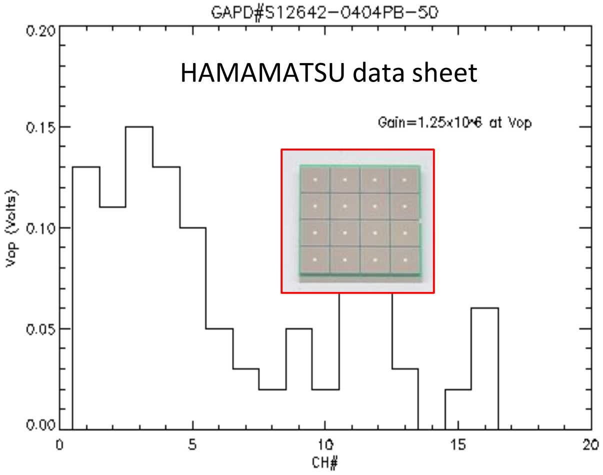


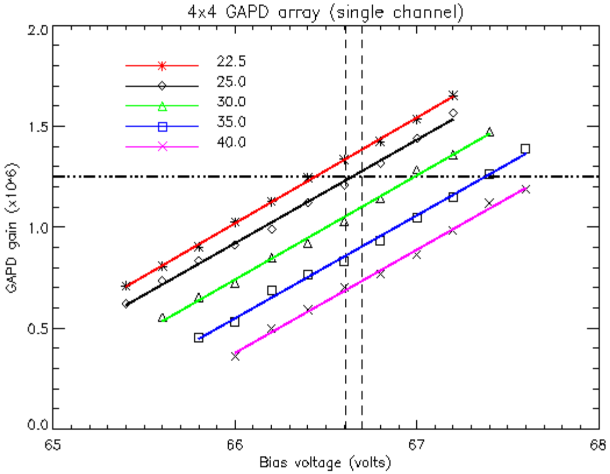
Channel #	Q/e (pc)	Gain	Bias (Volts)
CH#1	4.4	1.37×10^6	V_{bias}=71.6V (2.07Vo)
CH#2	4.1	1.28×10^6	
CH#3	4.1	1.28×10^6	
CH#4	3.95	1.23×10^6	

Gain variation of individual channel in 2x2 array GAPD is less than 5%.

GAPD gain : 4x4 G array

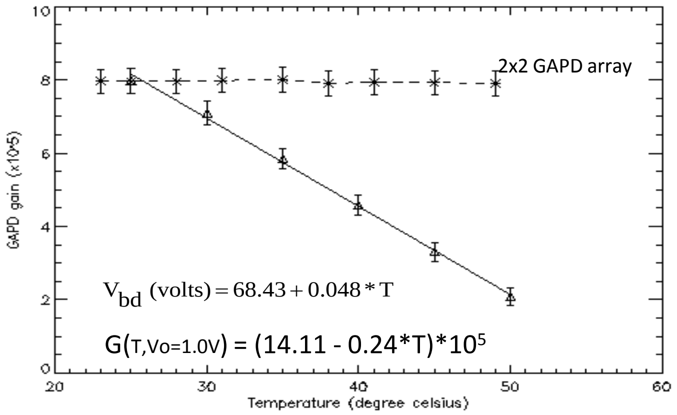
Gain : Measured vs HAMAMATSU data sheet





$G(V, T=25^{o}C) = (0.0007 + 0.51 * V_o) * 10^6$

GAPD Gain correction for temperature



$V_{bd}\ (\text{volts}) = 68.43 + 0.048 * T$

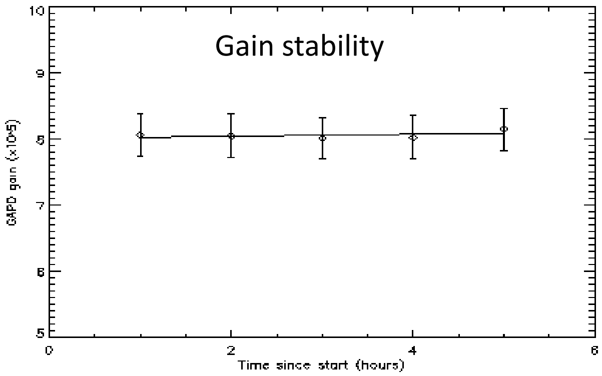
$G(T, V_o = 1.0V) = (14.11 - 0.24 * T) * 10^5$

$$G = \frac{C\,\Delta V}{q}$$

$$C_D = \frac{7.47\text{x}10^{5}\,\text{x}1.6\text{x}10^{-19}}{0.82} = 146 \text{ fm farad}$$

$$R_s \text{x} C_D = (50 \Leftrightarrow 1000)\text{x}146\text{x}10^{-15} = 7.3\,ps \Leftrightarrow 146\,ps$$

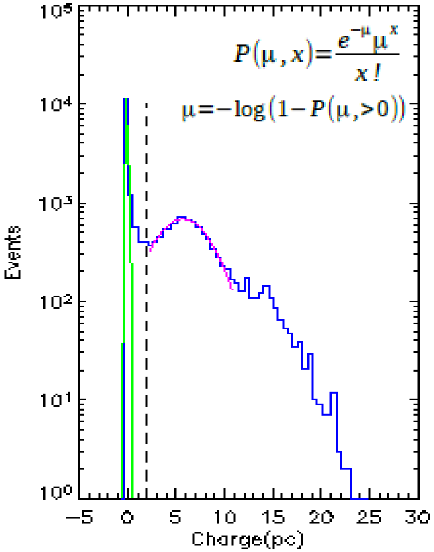
$$R_Q \text{x} C_D = 220\text{x}10^{3}\text{x}146\text{x}10^{-15} = 32.1\,ns$$

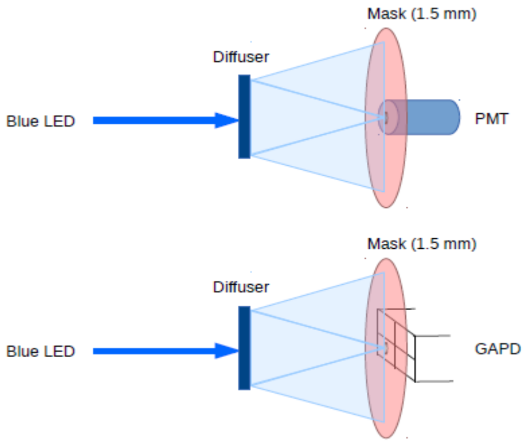


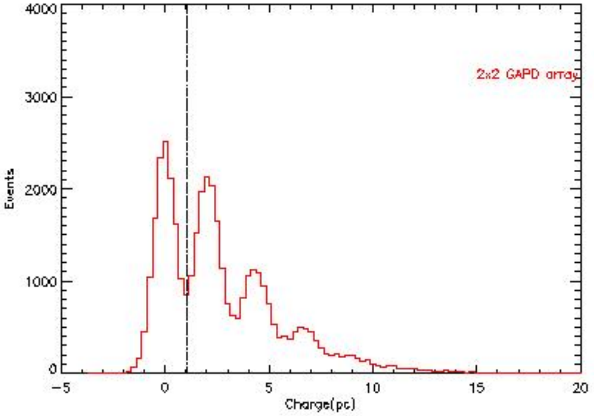
Photon Detection Efficiency (PDE)

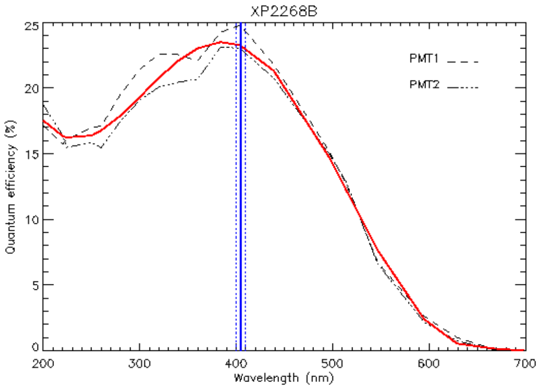
PMT : Quantum efficiency $$\eta = \frac{\text{photoelectrons}}{\text{incident photons}}$$

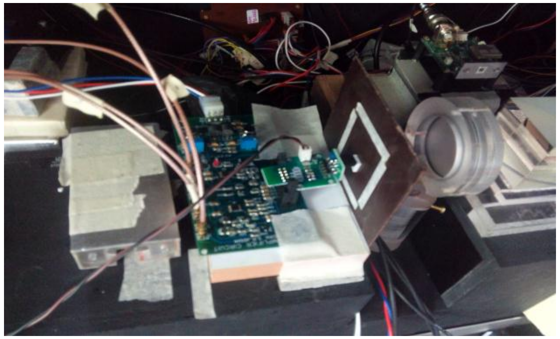
GAPD : Photon detection efficiency $$PDE(\eta) = \text{QE} * \text{P}_{\text{AT}} * \varepsilon_{gem}$$

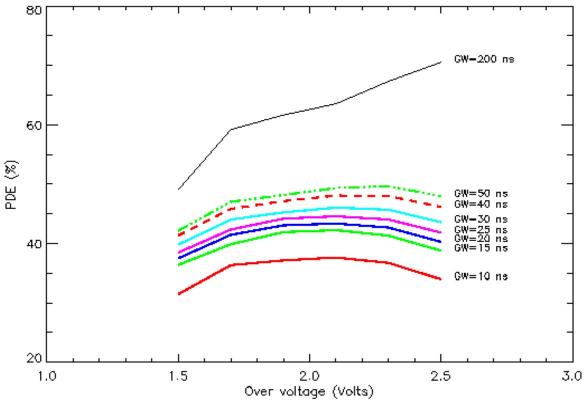












Average QE of PMT @ 405 nm = 23.22 %
Average PE detected by PMT = 0.53 ± 0.03
Average number of incident photons on PMT photocathode = 2.28 ± 0.10 (10% error in QE)

Photoelectron ID	Counts	Poisson probaibilty	Total counts	Mean PE (μ)	
0-PE (Pedestal)	13953	$P(\mu,0)=e^{-\mu}$	40000	$P(\mu,1)/P(\mu,0)$	μ = 0.97
1-PE	13494	$P(\mu,1)=e^{-\mu}\,\mu$		$P(\mu,2)/P(\mu,1)$	μ = 1.18
2-PE	7933	$P(\mu,2)=(e^{-\mu}\,\mu)/2$		$P(\mu,0)$	μ = 1.05

Summary

- GAPD pulse profile : Rise time~7ns, Decay time ~30ns,
  Quench resistor ~220 KΩ, C_d ~ 146fm farad
- Dark count rate : 1 MHZ for > 0.5 pe @ 1.0 volt V_o,
  after pulsing rate 13.5 % for 100ns gate width.
- Break down voltage and its temperature dependence.

$$V_{bd}\,(\text{volts}) = 68.43 + 0.048 * T$$

- Absolute gain

$$G(V, T=25^{o}C) = (0.0007 + 0.51 * V_o) * 10^6$$

$$G(T, V_o=1.0V) = (14.11 - 0.24 * T) * 10^5$$

- Photo Detection Efficiency (PDE) : Average PDE 36-40%
  for 10-15 ns gate window @ Vo=2V
- Probability of avalanche ~80-85% at above overvoltage.