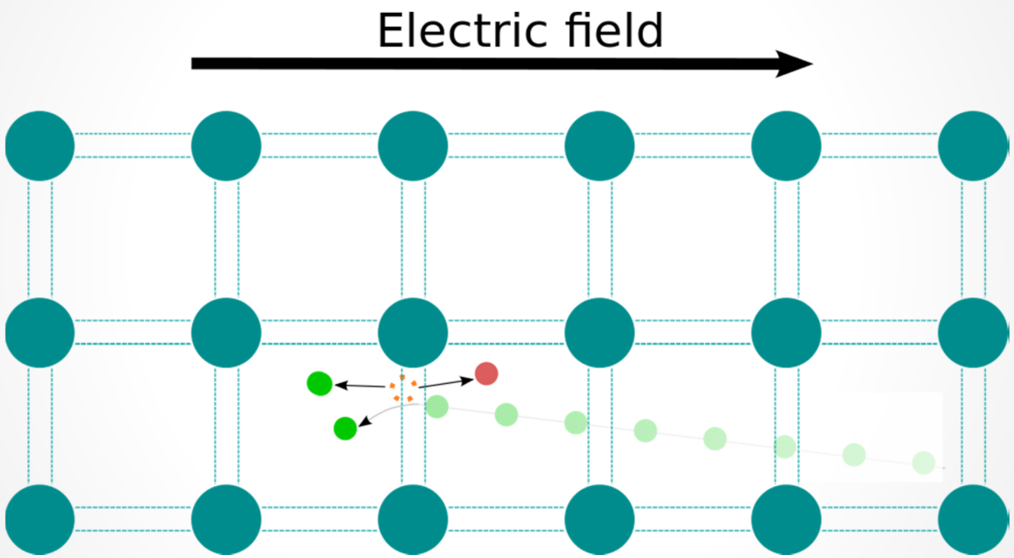
SPAD

Single Photon Avalanche Diode

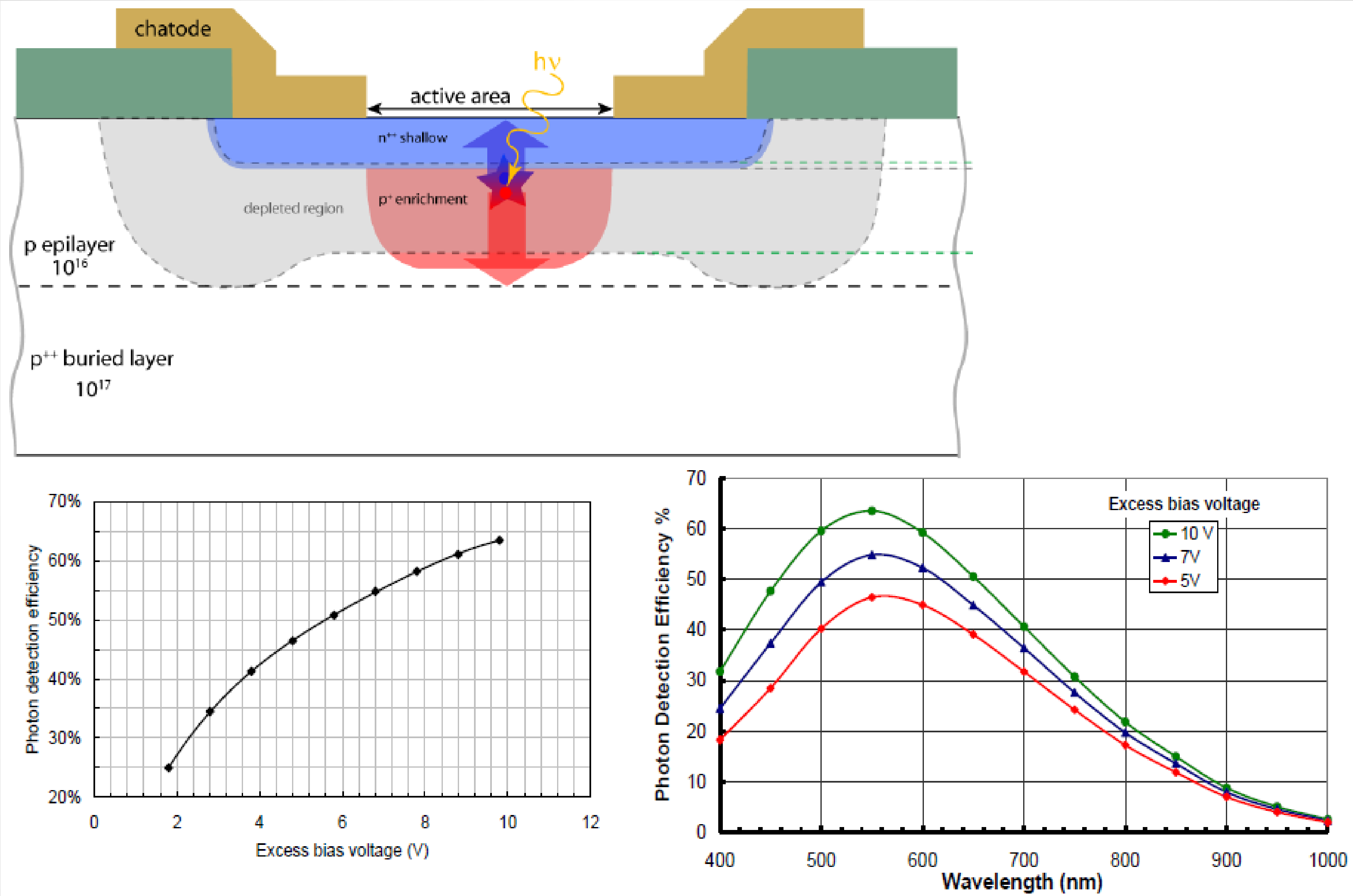
Avalanche Photodiode(APD)

Avalanche effect



http://en.wikipedia.org/wiki/Impact_ionization

Geiger-mode APDs(single photon avalanche diode)



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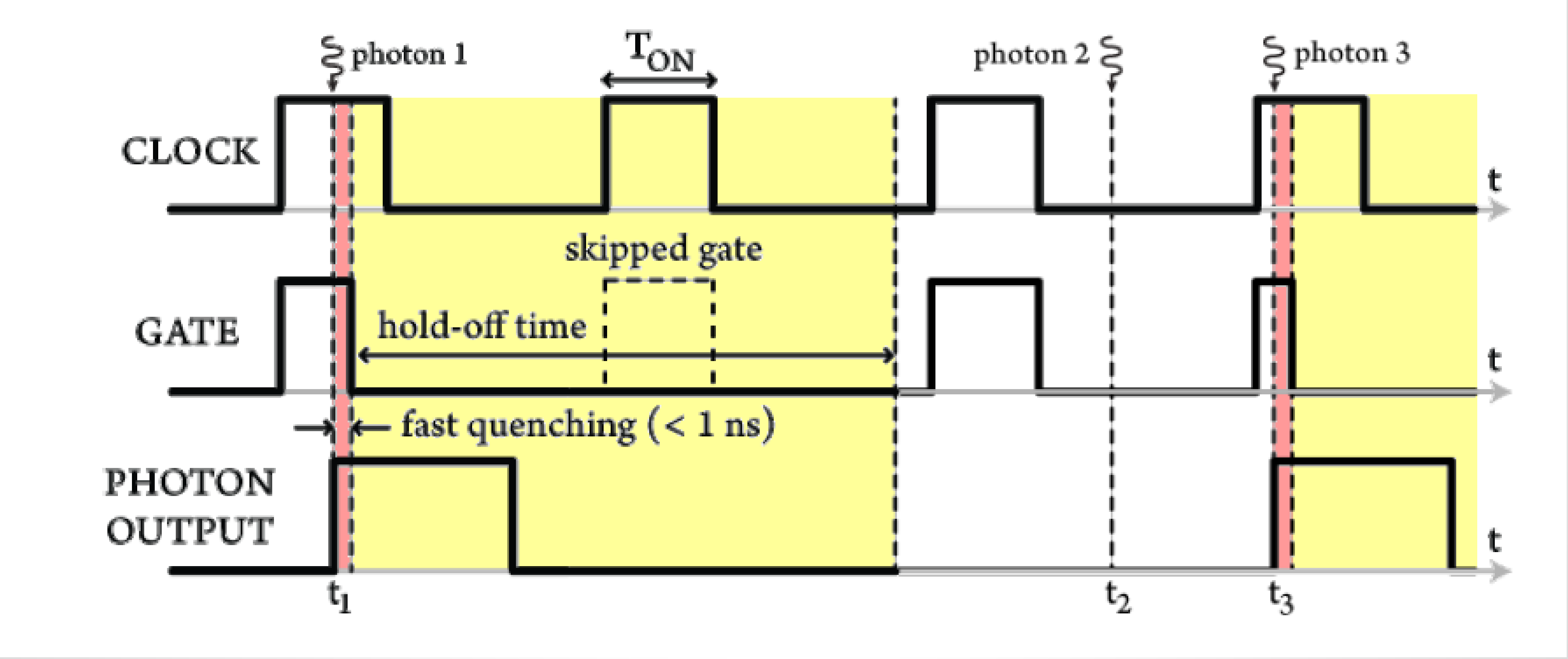
Geiger-mode APDs(single photon avalanche diode)



Operating Conditions and Performance

Single-photon counting resolution

The intensity of the signal is obtained by counting (photon counting)
the number of output pulses within a measurement time slot,
while the time-dependent waveform of the signal is obtained by measuring the time distribution of the output pulses (photon timing).

Dark count

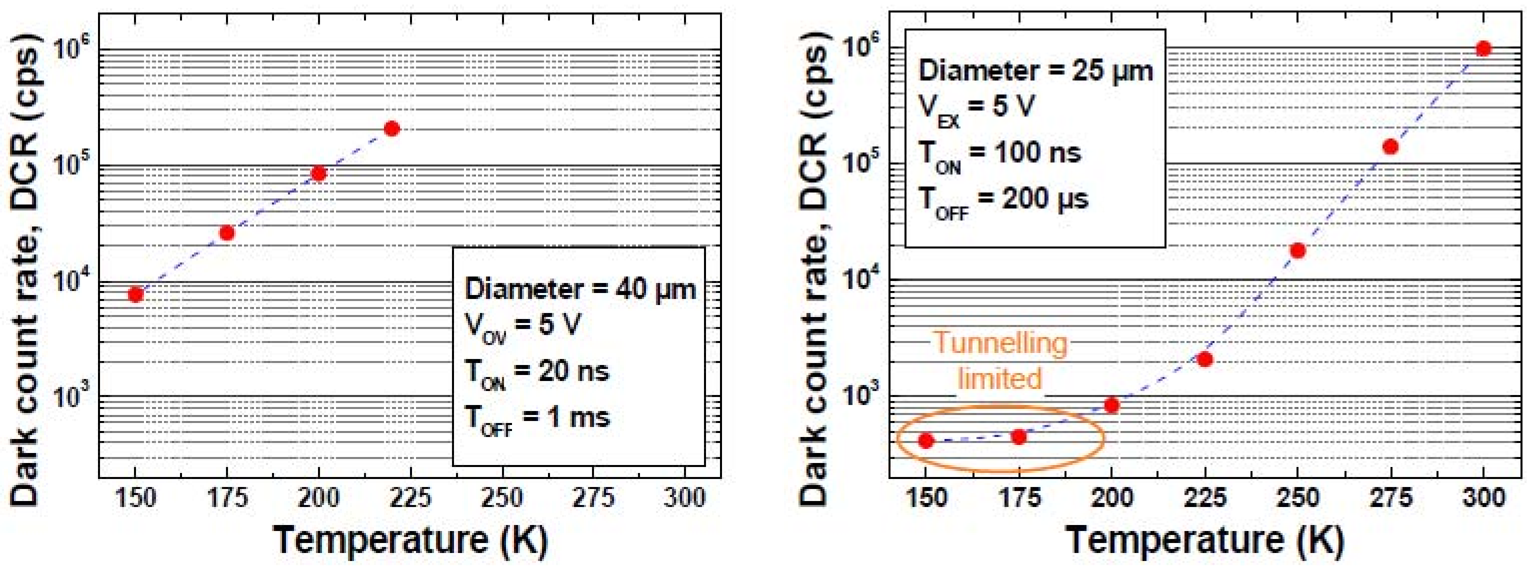
photon-generated carriers, thermally-generated carriers (through generation-recombination processes within the semiconductor) can also fire the avalanche process.
Therefore, it is possible to observe output pulses when the SPAD is in complete darkness.
The resulting average number of counts per second is called dark count rate

Operating Conditions and Performance

$$DCR = -\frac{1}{T_{ON}} \cdot \ln\left(1 - \frac{N_{counter}}{f_{GATE}}\right)$$

where $f_{GATE} = 1/(T_{ON}+T_{OFF})$ is the gate frequency and $N_{counter}$ is the avalanche rate in gated mode as measured by a photon counter.

$In_{0.53}Ga_{0.47}As/InP$ SPAD.



Proc. of SPIE Vol. 7222 72221G-4

Operating Conditions and Performance

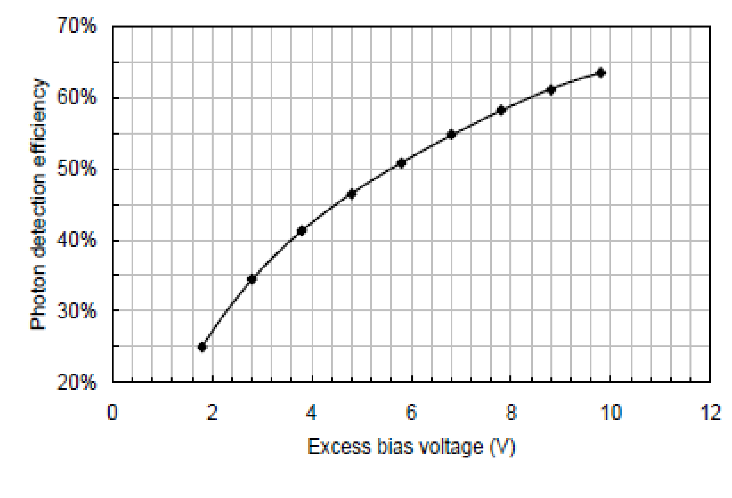
PDE(Photon Detection Efficiency) Probability of photon absorption and avalanche triggering

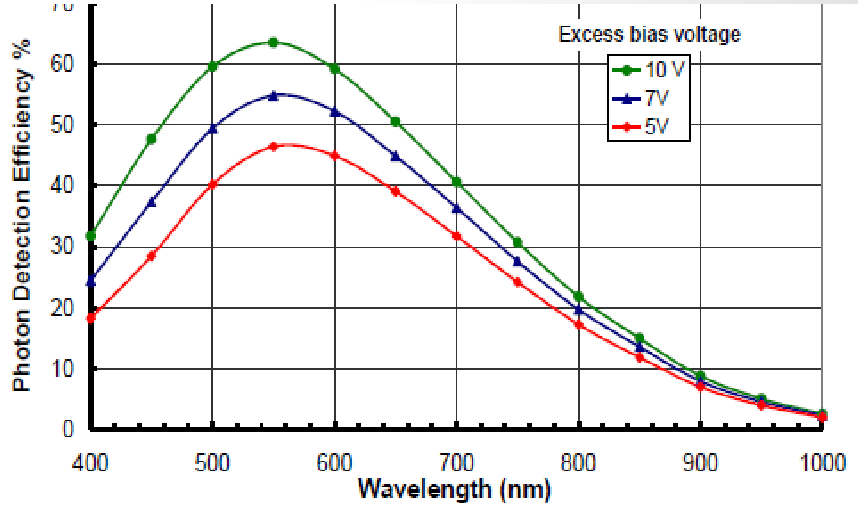
$$PDE = QE \times \varepsilon_{geom} \times \varepsilon_{Geiger}$$

QE quantum efficiency, function of the incident photon wavelength

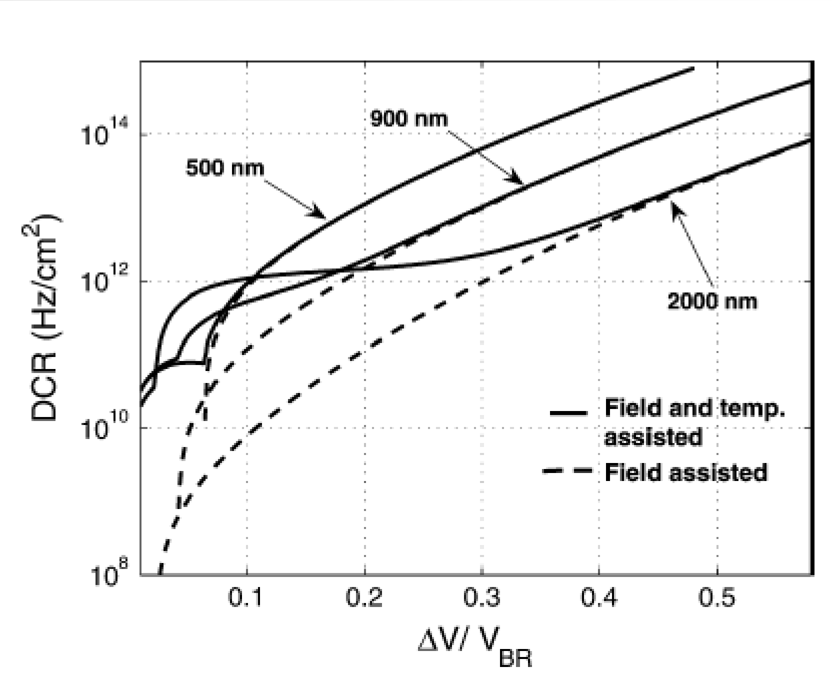
ε_{geom} geometrical factor (fill factor) indicating which fraction of the device is sensitive to photons

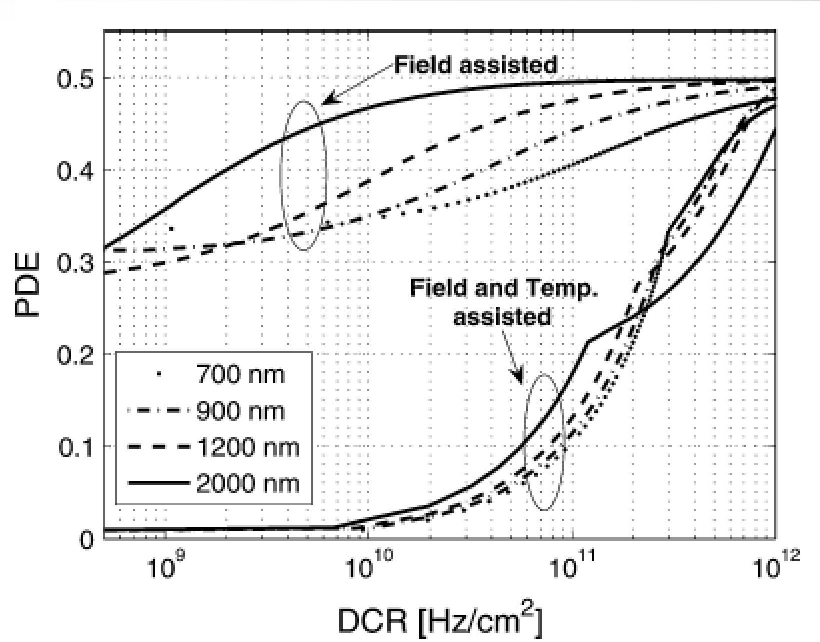
ε_{Geiger} probability to trigger a Geiger discharge





Operating Conditions and Performance



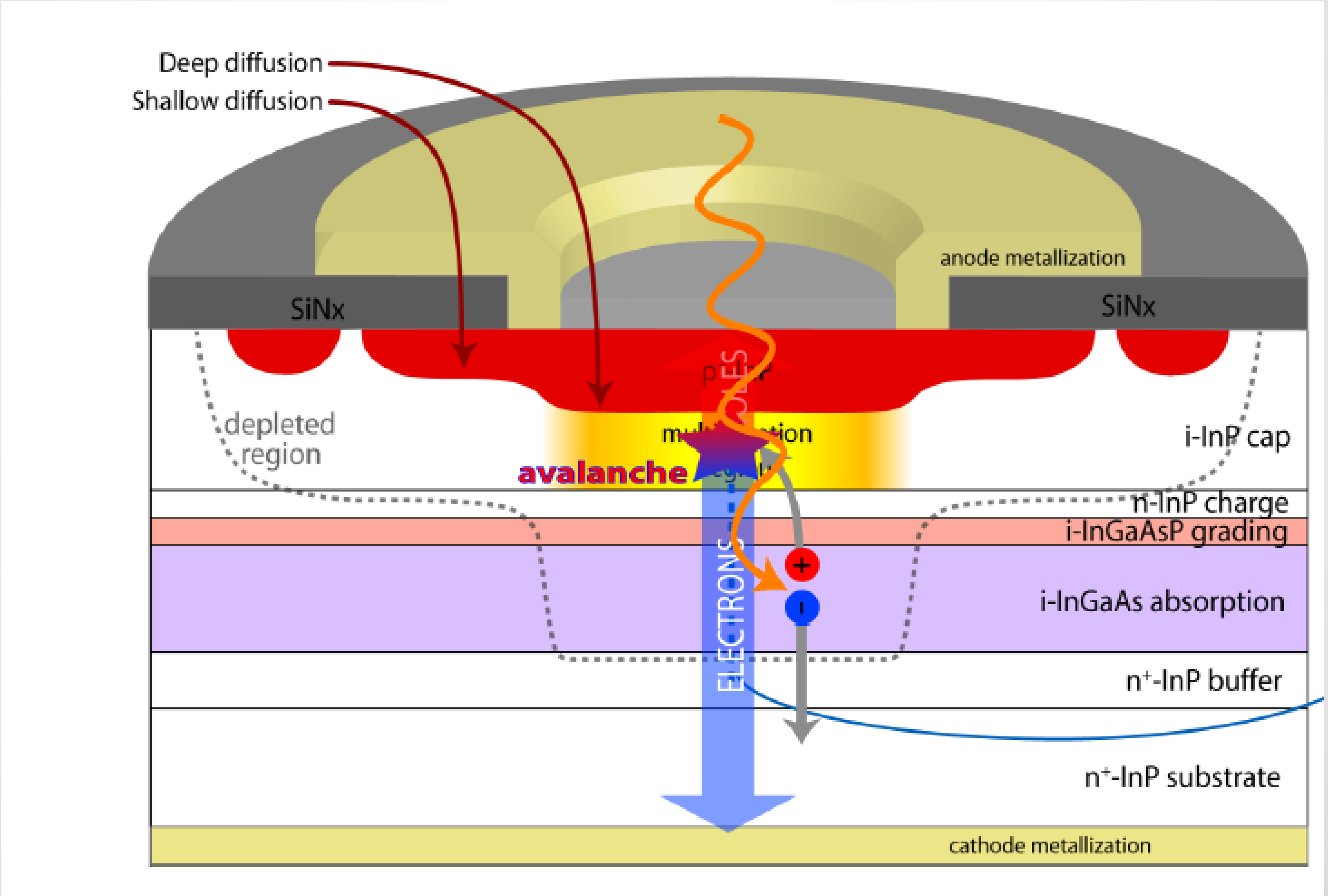


IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 44, NO. 12, DECEMBER 2008

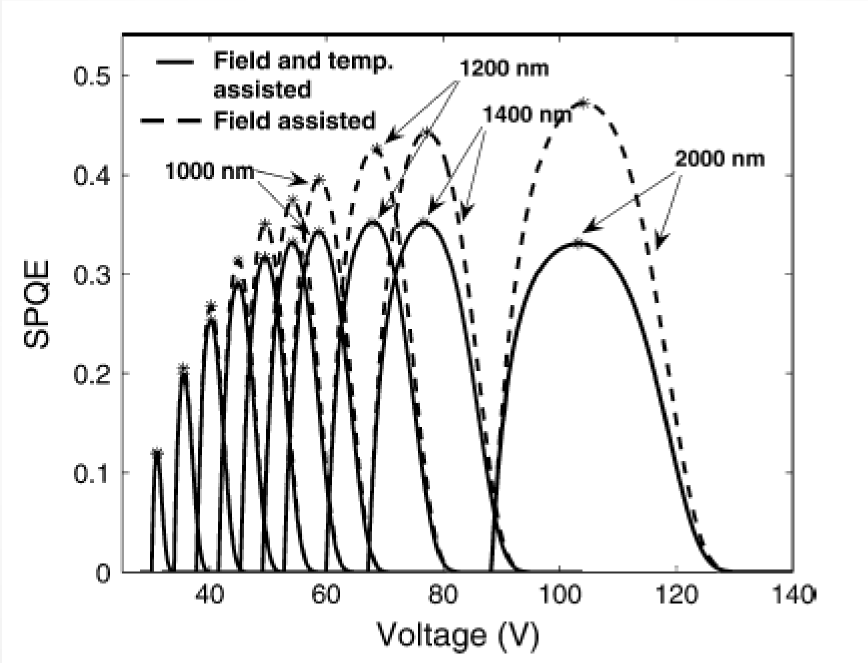
InP multiplication regions of 700, 900, 1200, 2000nm

InGaAs absorption layer of 1um

Operating Conditions and Performance



Operating Conditions and Performance



SPQE versus applied voltage for several widths of the multiplication region. The maximum achievable value of the SPQE curve is determined by the quantum efficiency, which in this case is 0.5.

Catalog spec

Perkin-Elmer

Table 1. **Specifications SPCM-AQ4C at 22°C, all models, unless otherwise indicated**

Note: *At power on and 40°C
**At maximum count rate

Parameter		Minimum	Typical	Maximum	Units
Supply currents:	at +2 V		1.0	4.0* 3.0**	Amps Amps
	at +5 V		0.20	1.0**	Amps
	at +30 V		0.01	0.04**	Amps
Maximum power consumption	at +2 V		2	6**	Watts
	at +5 V		1	5**	Watts
	at +30 V		0.3	1.2**	Watts
Supply voltages		1.95	2	2.05	V
		4.75	5	5.25	V
		29	30	31	V
Operating temperature (heatsink)		5		40	°C
Photon detection efficiency (per channel)	at 400nm	1	2.5		%
	at 650nm	45	60		%
	at 830nm	35	45		%
	at 1060nm	1	2		%
Average Pd variation per channel at constant heat sink temperature (6 hrs at 25°C)			±1	±3	%
Average Pd variation per channel at 5°C to 40°C heat sink temperature			±4	±10	%
Dark count (per channel)				500	Counts/Sec.
Average dark count variation per channel at constant heat sink temperature (6 hours at 25°C)				±10	%
Average dark count variation per channel at 5°C to 40°C heat sink temperature				±20	%
Dead time (Count rates below 5 Mc/s) nanoseconds			50		ns
Output pulse width			25		ns
Maximum count rate (per channel)	Continuous		1.5		Mc/s
	500ms duration, 25% duty cycle		4		Mc/s
Afterpulsing probability			0.3	0.5	%
Gate threshold voltage (at V_{Sup}= 5V)	Low level (sink 5mA) = Gate On		0	0.4	V
	High level = Gate Off		3.5	5.25	V
Gate turn-on delay before first edge of true output pulse			60	75	ns
Gate turn-off delay for minimum last output pulse width of 10ns			4	15	ns
Linearity correction factor [7] See fig. 3	at 200 kc/s		1.01	1.10	
	at 1 Mc/s		1.08	1.15	
	at 1.5 Mc/s		1.12	1.20	

Catalog spec

Perkin-Elmer

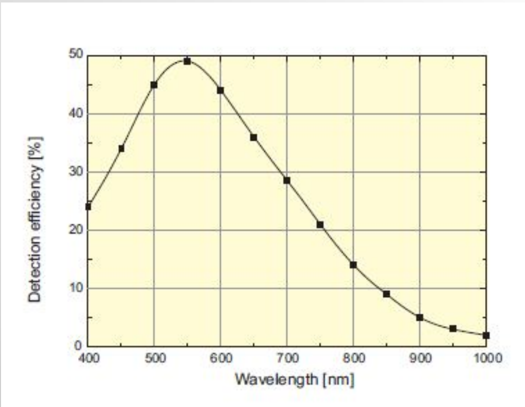
Table 1. Absolute Maximum Ratings

Supply voltage [(1)]	5.5 V
Maximum count rate	Maximum count rate can be sustained if case temperature is maintained within limit specified limits.
Peak light intensity	10^4 photons per pulse and pulse width < 1 ns
Case temperature [(3)]	-20°C/+70°C storage, +5°C /+70°C operating

Parameter	Min	Typ	Max	Unit
Active area (diameter) at minimum PDE	170	180		µm
Photon detection efficiency (PDE) (without FC adaptor)[(2)] at: 650 nm 830 nm		 75 50		 % %
Dark Count SPCM-AQRH-10 SPCM-AQRH-11 SPCM-AQRH-12 SPCM-AQRH-13 SPCM-AQRH-14 SPCM-AQRH-15			1500 1000 500 250 100 50	Counts / second
Single photon timing resolution (at 825 nm)[(2,3)] Contact factory for optimized timing below 200 ps and at other wavelengths		225	250	ps
Dead time (count rate below 5M/c) Other values can be factory set		60		ns
Output count rate before saturation		12		Mc/s
Linearity correction factor at 200 Kc/s 1 Mc/s 5 Mc/s 10 Mc/s		1 1.02 1.16 1.40		
Afterpulsing probability		1.0	3.0	%

Catalog spec

PicoQuant



Specifications (@ 25 °C)

Dark Counts (typical) . . . . 20 µm SPAD . . . . 50 µm SPAD . . . . 100 µm SPAD
Non-cooled version . . . . < 250 cps . . . . < 5.000 cps . . . . < 20.000 cps
Cooled version . . . . < 25 cps . . . . < 50 cps . . . . < 250 cps

Single Photon Timing Resolution
TTL counting output (FWHM) . . . . 250 ps
NIM timing output (FWHM) * . . . . down to 50 ps, increases in blue/UV spectral range

Afterpulsing Probability . . . . < 3 % (typical)

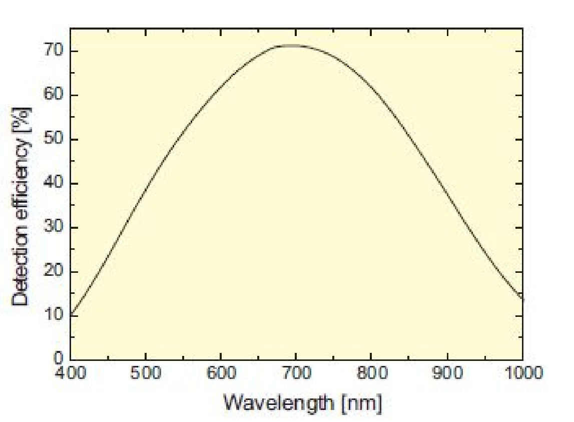
Input/Output
Dead time . . . . 77 ns (typical)
Output signal . . . . TTL for counting output, NIM for timing output *
Output pulse rise and fall times . . . . < 2 ns on 10 pF load
Output pulse duration . . . . 20 ns (typical)
Gating input . . . . TTL control (low level gates detector off)
Supply input connector . . . . standard 3.5 mm supply socket

Supply Voltage . . . . unregulated DC, any value 5 V - 12 V

** Available as an option*

Catalog spec

PicoQuant



Specifications (@ 25 °C)

Spectral range . . . . 400 nm - 1100 nm
Active area diameter . . . . 150 μm
Photon timing resolution*. . . . . 350 ps - 800 ps (FWHM, depending on module, wavelength and signal rate)
Afterpulsing probability (0 to 500 ns)* . . . . < 1 % (typical)
Dead time . . . . < 70 ns (typical)
Fiber connector type (optional) . . . . FC/PC

Dark Count Rate
τ-SPAD-20 . . . . < 20 cps (available upon request)
τ-SPAD-50 . . . . < 50 cps
τ-SPAD-100 . . . . < 100 cps

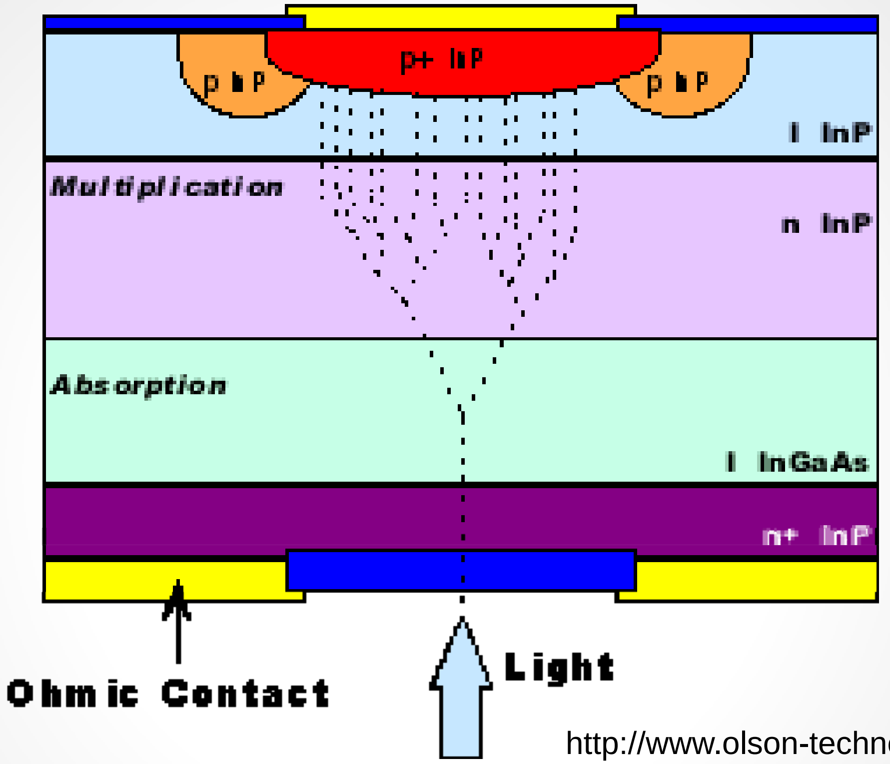
Photon Detection Efficiency* (typical values, without fiber connector)
@ 405 nm . . . . 10 ± 5 %
@ 470 nm . . . . 30 ± 5 %
@ 670 nm . . . . 70 ± 5 %
@ 890 nm . . . . 35 ± 5 %
Losses due to fiber connector: approx. 10 % absolute

Input/Output
NIM output
Pulse width . . . . 15 - 25 ns
Pulse amplitude . . . . -0.8 V to -1 V (into 50 Ohms)
Connector type . . . . SMA
TTL output
Pulse width . . . . 15 - 25 ns
Pulse amplitude . . . . > 2.4 V (into 50 Ohms)
Connector type . . . . Lemo, type EPS.00.250
Gating input
Input voltage . . . . TTL control, TTL high (> 2.4 V) enables counting
Response time. . . . . disable: < 40 ns (typ. 20 ns); enable: < 100 ns (typ. 85 ns)
Connector type . . . . SMA

Operating Conditions
Supply voltage . . . . 12 V
Supply current . . . . 1.5 A (at turn on), 0.3 A (at 1 Mcps)
Operating temperature . . . . 10 °C - 40 °C

** measured by illuminating < 30 μm in the center of the active area*

Avalanche Photodiode(APD)



http://www.olson-technology.com/mr_fiber/glossary-a.htm

Linear operation below breakdown voltage (V_{bd})

output charge ∝ number of e-h pairs ∝ number of incident photons

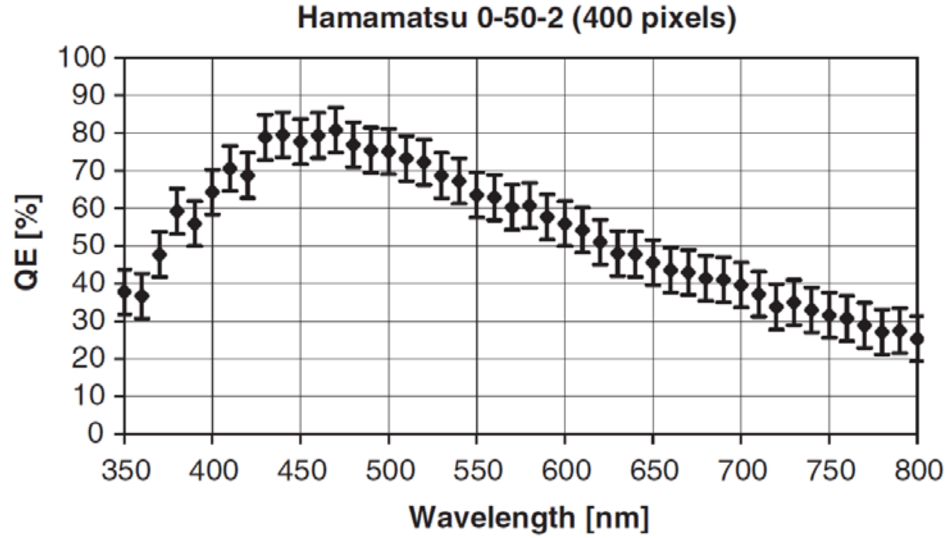


Fig. 12. Quantum efficiency as function of the wavelength.

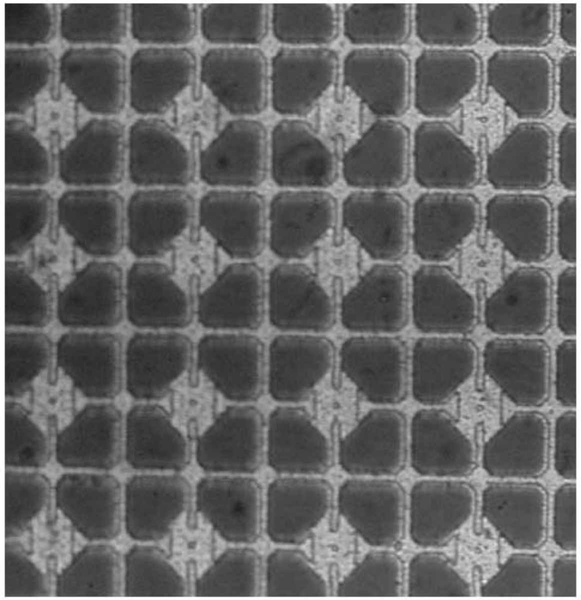
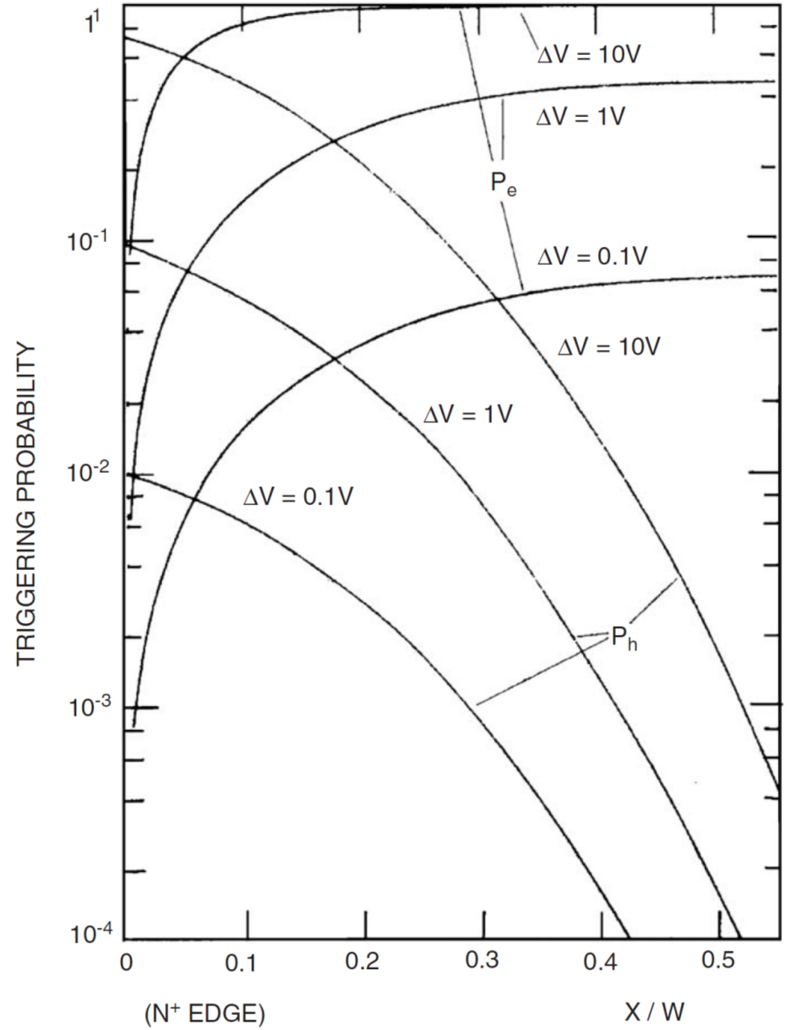


Fig. 13. Microscopic view of a G-APD produced at JINR in Dubna, Russia.



Photodiode characteristic

- Photo sensitivity $$s = \frac{i_s}{p} \ (A/W)$$
- Dark current
  - Photodiode에 빛을 비추지 않았을 때 흐르는 역전류
- Shunt resistance $$R_{sh} = \frac{V_{reverse}}{I_d} \ (\Omega)$$
- Terminal capacitance
  - Photodiode 내부 전기 용량
- Rise time (Tr) , Cut-off frequency
  - 외부 신호에 의한 회로의 출력이 10%에서 90%까지 오르는데 걸리는 시간
  - PD가 체크할 수 있는 최대 주파수

Photodiode의 성능을 나타내는 주요 특성

빛에 대한 반응 성능과 noise의 발생 및 반응 속도에 직접적인 영향을 준다.

Photodiode에 역전압을 걸어주거나 PN접합 사이에 다른 물질을 삽입하여 성능을 개선할 수 있다.

Operating Conditions and Performance

G-APD response

$$A = N_{\gamma}^{in} \times PDE \times g \times (1+\varepsilon) \times (1+P_{AP})$$

N_{γ}^{in}	number of incident photons
g	gain
ε	cross-talk probability
P_{AP}	the after-pulse probability

g, PDE, ε, and P_{AP} are all increasing with V_{bias}

implying a complex dependence of the G-APD response on the bias voltage

Catalog spec

Perkin-Elmer

Figure 1. **Detector scan without FC fiber adaptor**

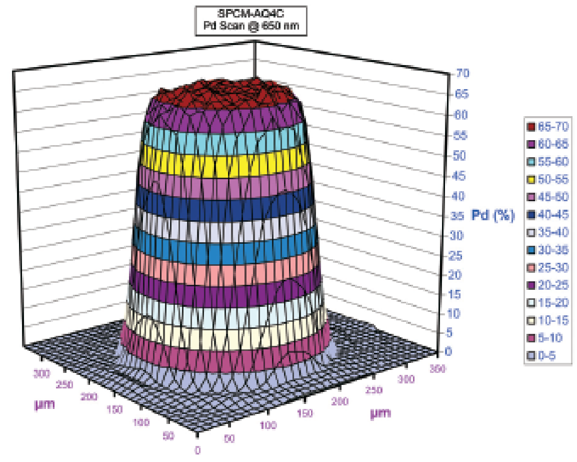


Figure 2. **Photon detection efficiency (pd) vs. wavelength**

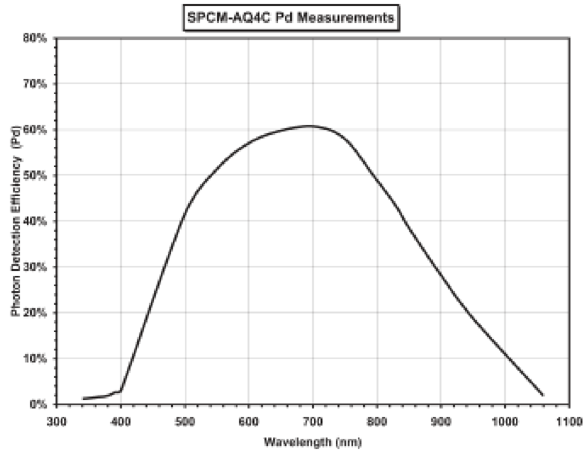


Figure 3. **Typical correction factor**

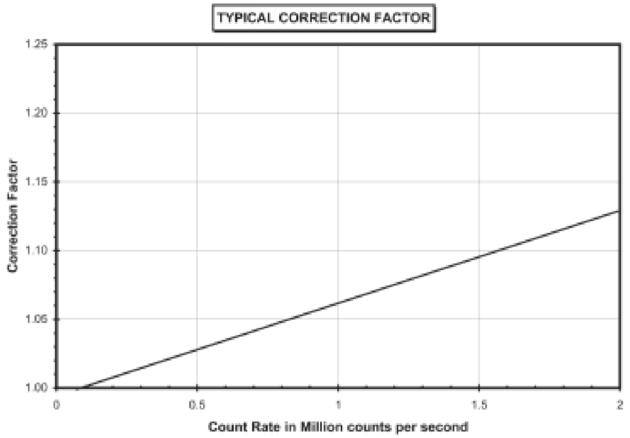
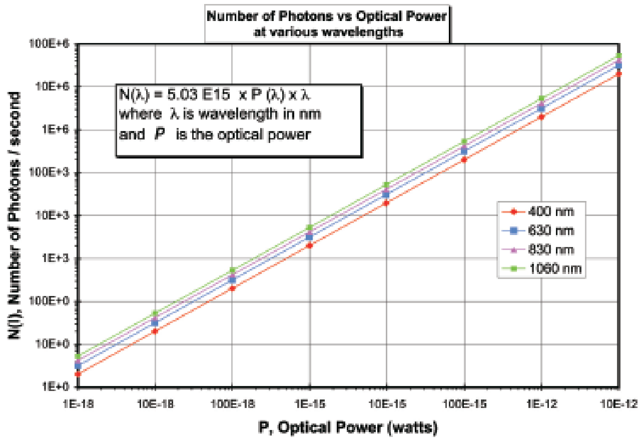


Figure 4. **Optical power vs. number of photons**



Catalog spec

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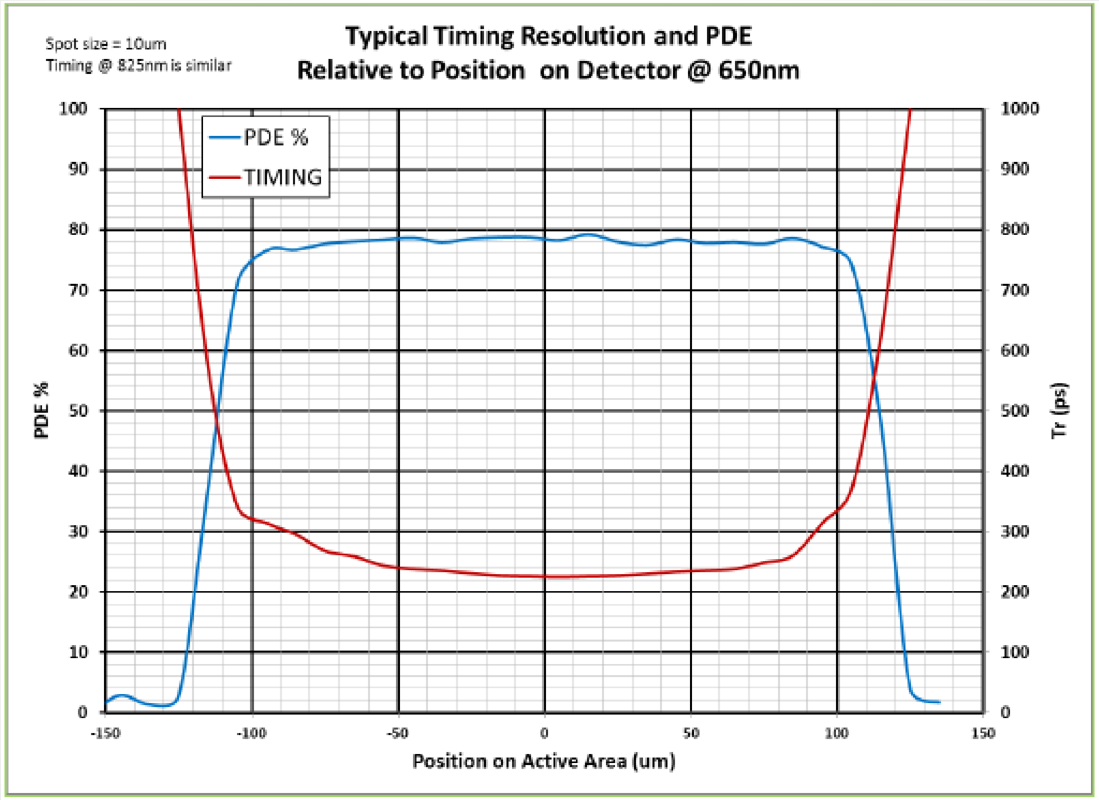
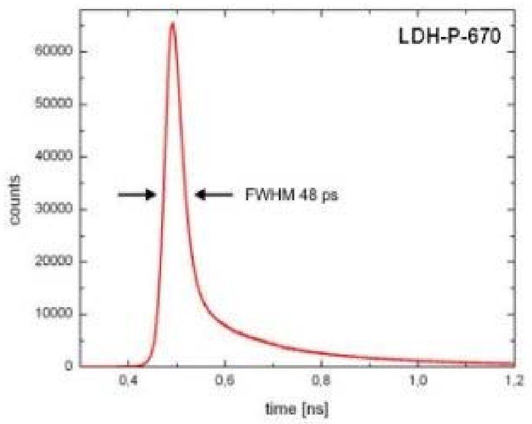
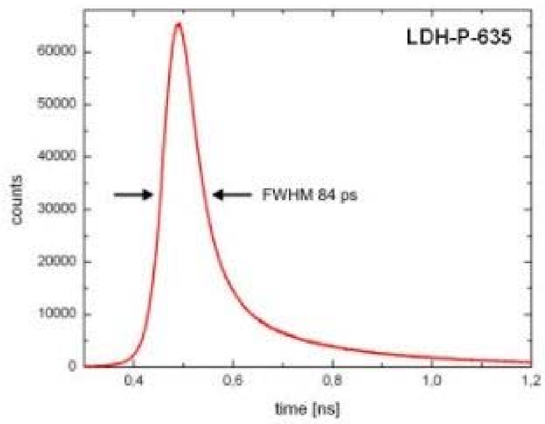


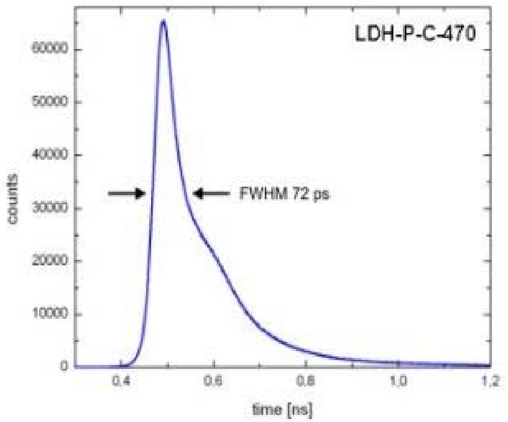
The graphs below show examples of the measured instrument response functions (IRF) of a PDM module with an active area of 50 µm. The measurements were taken with the PicoHarp 300 TCSPC module and different laser heads of the LDH series driven by the PDL 800-B.



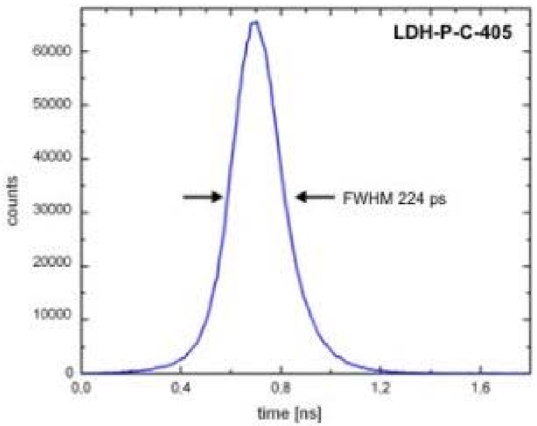
The measured full width at half maximum (FWHM) is 48 ps for the excitation at 670 nm. Taking the exceptionally short pulse width of the excitation laser of 32 ps into account, this results in a timing response of the SPAD of 37 ps.



The measured full width at half maximum (FWHM) is 84 ps for the excitation at 635 nm. Taking the pulse width of the excitation laser of 66 ps into account, this results in a timing response of the SPAD of 50 ps.



The measured full width at half maximum (FWHM) is 72 ps for the excitation at 470 nm. Taking the pulse width of the excitation laser of 56 ps into account, this results in a timing response of the SPAD of 44 ps.



The measured full width at half maximum (FWHM) is 224 ps for the excitation at 405 nm (laser pulse width: 60 ps). Such an increase of the IRF at blue/UV wavelengths is typical for these SPADs.