CMOS Single Photon Detectors

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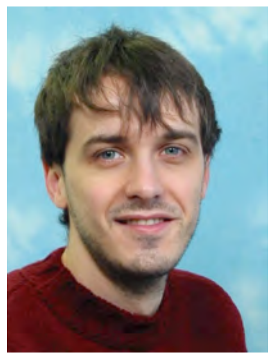
Acknowledgements

The <u>AQUA Group</u> was started in June 2003. It is funded by the Swiss National Science Foundation and Logitech

Cristiano Niclass



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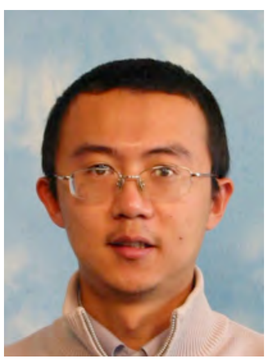

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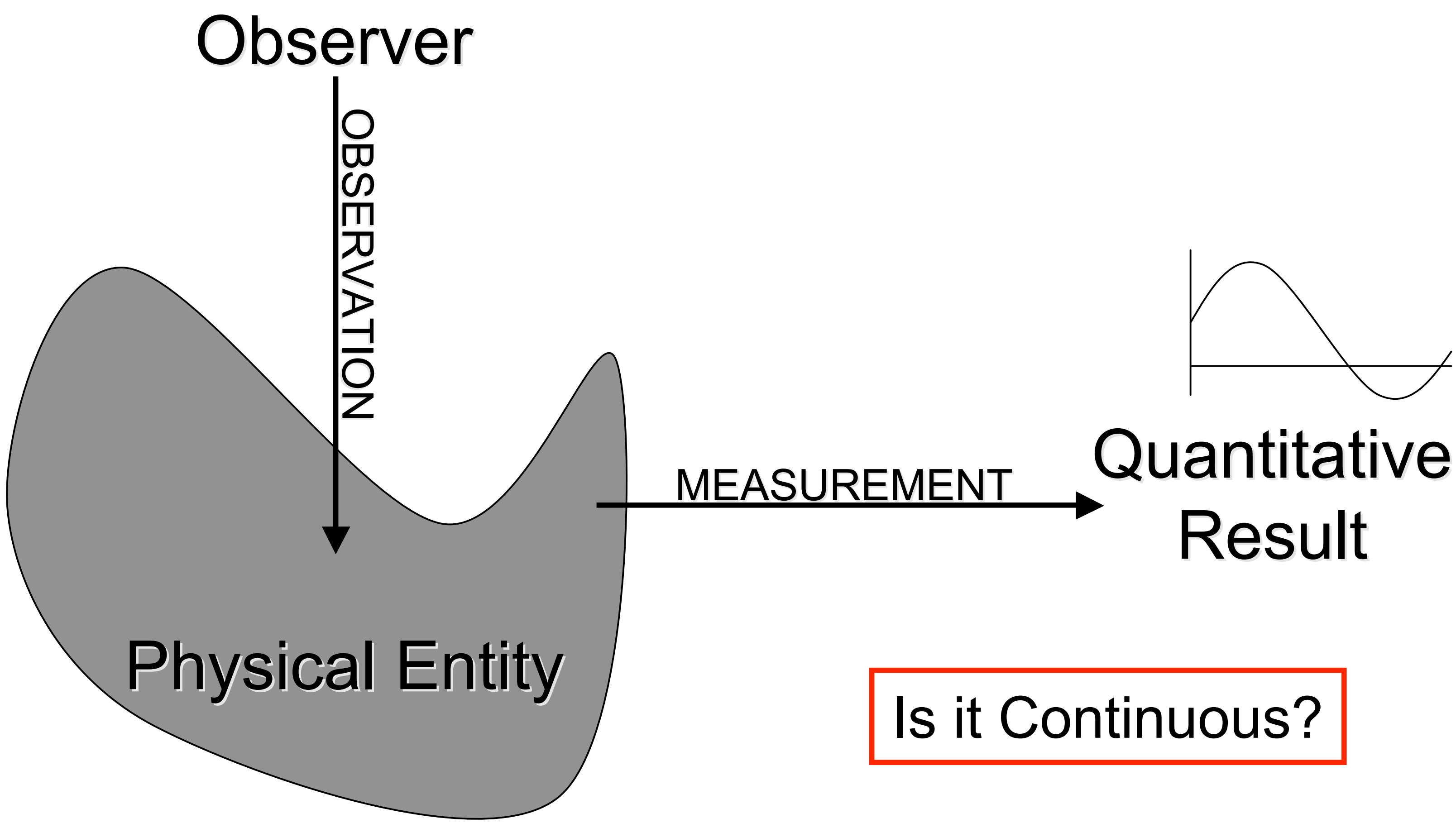
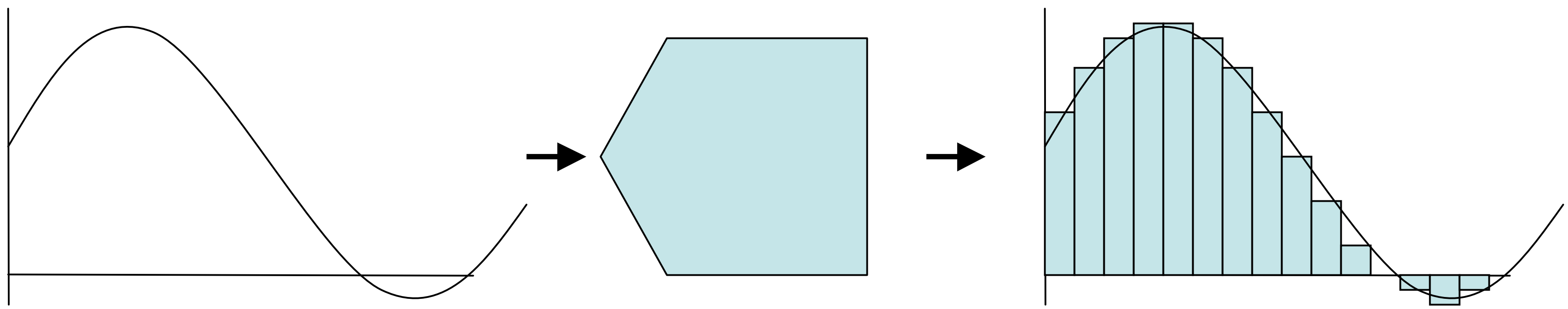
The World Is Analog



Is it Continuous?

Typical Measurement Process



Quantization in time and amplitude

In Reality…

- The world is not analog but measurable by quanta
- The analog measurement is the result of a conversion of the true signal
- Every conversion introduces errors

Quanta → Analog Signal → Digital

Why not Skipping Analog?

Quanta → Digital

<u>Example</u>:

photons → digital pulses

Outline

- Why, when, where?
- Single Photon Avalanche Diodes (SPADs)
- 3D Imaging
- 2D Imaging
- Conclusions & future work
- Acknowledgements

Why, When, Where?

Why Do We Care?

- Single photon detectors (SPDs) are entering the mainstream
- They will be found in medium to high volume applications

Examples:

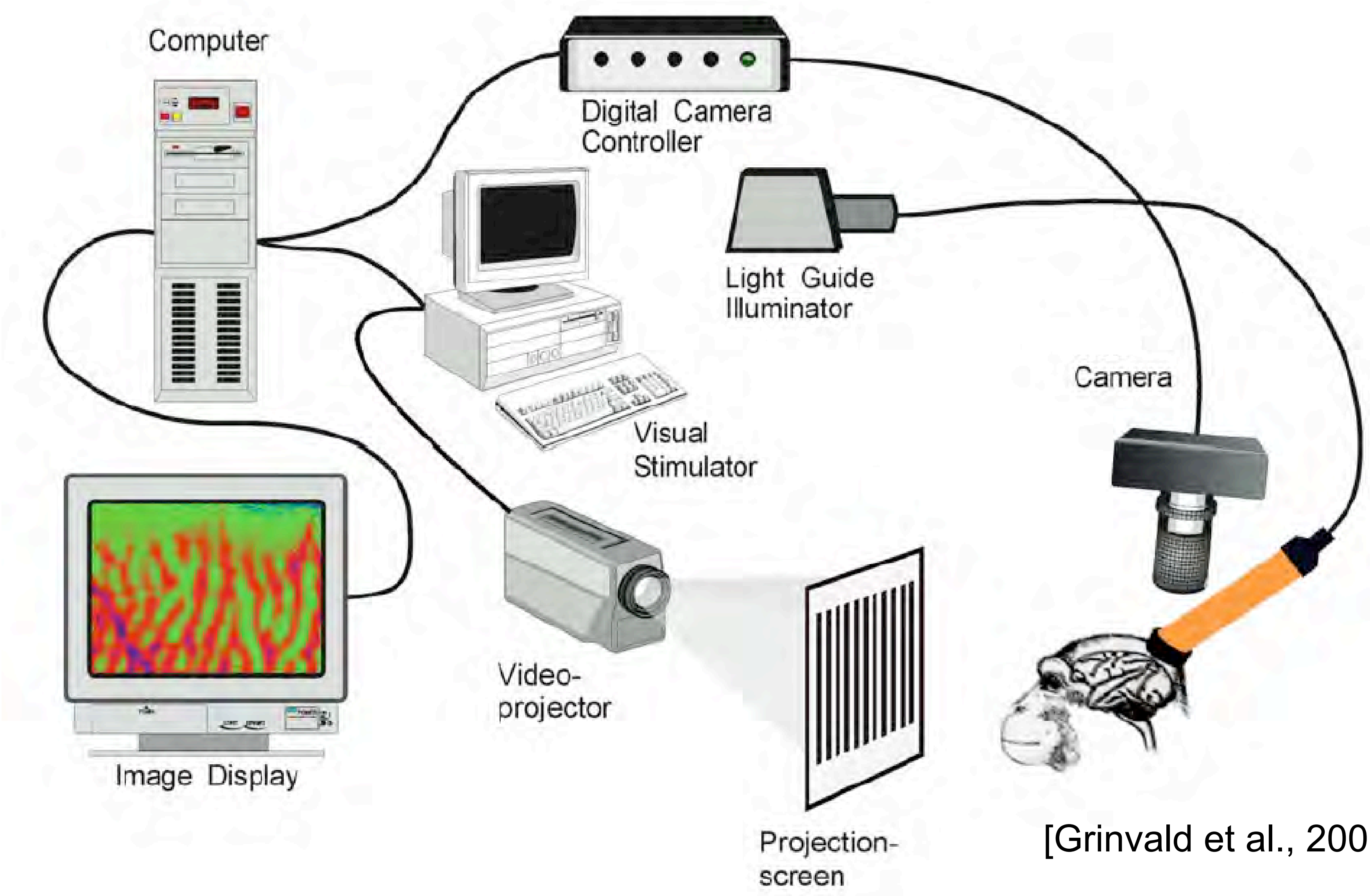
- Secure Telecom (private key distribution systems) [Gisin/UniGe, IdQuantique, SensL]
- Optical Telecom [Boser/UCB, Pister/UCB, Dust Networks]
- True Random Number Generators [Popovic/EPFL, IdQuantique]
- High sensitivity (L^3) videocams [Cork Univ., QinetiQ, e2v]
- 3D videocams for gaming applications [***]
- Low dose X-ray imaging [Hamamatsu, Fairchild Imaging]

SPDs in Science

- Molecular count/detection
- Neuro-activity scanning (dye[1]-based)
- Fluorescence correlation spectroscopy (FCS)
- Two-photon spectroscopy
- Fluid-dynamics research
- Non-ionizing imaging (transillumination)

1) Dye is a substance composed of nanoparticles which change reflectivity depending on potential

Neuro-activity Scanning



[Grinvald et al., 2001]

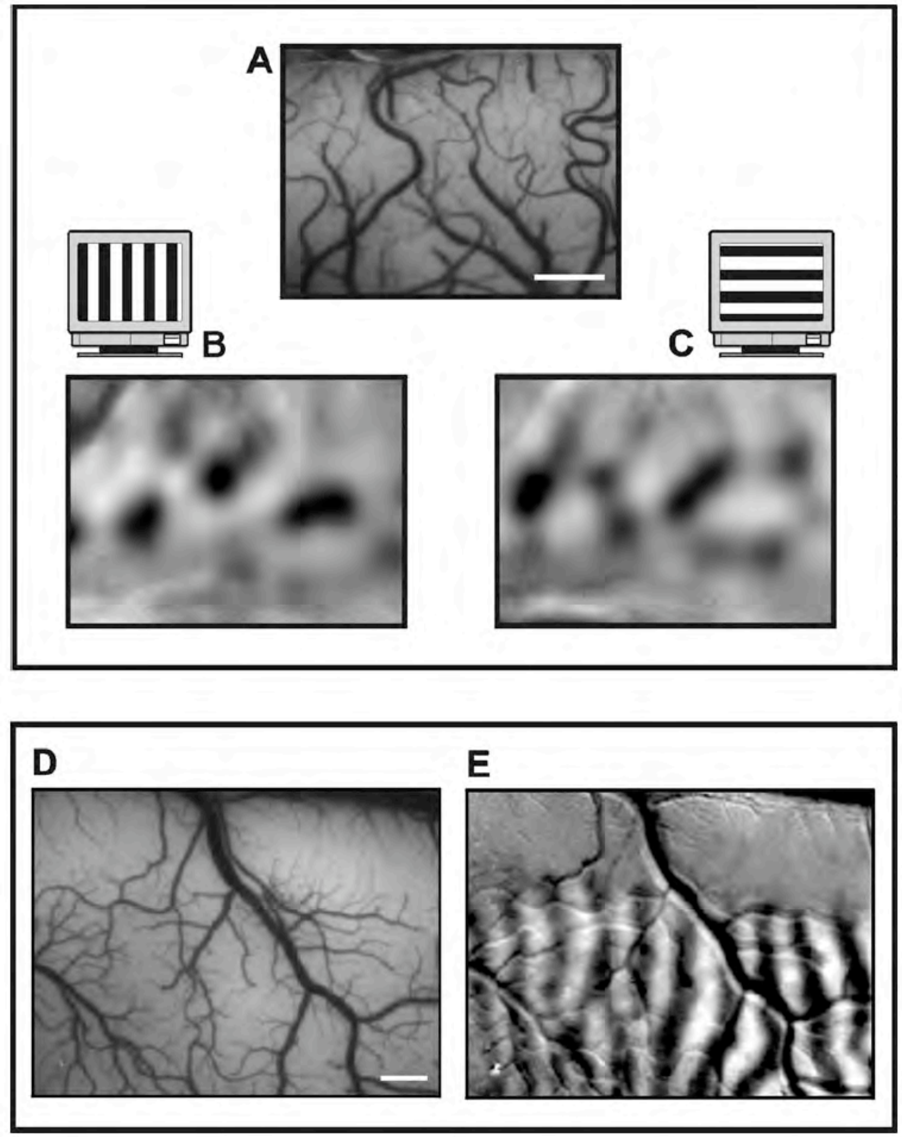
Neuro-activity Scanning (Cont.)

$\Delta I \approx 10^{-3} I$

for $\Delta I >> \sigma^2(I) = I^{1/2}$

→ must work with ultra-high intensities

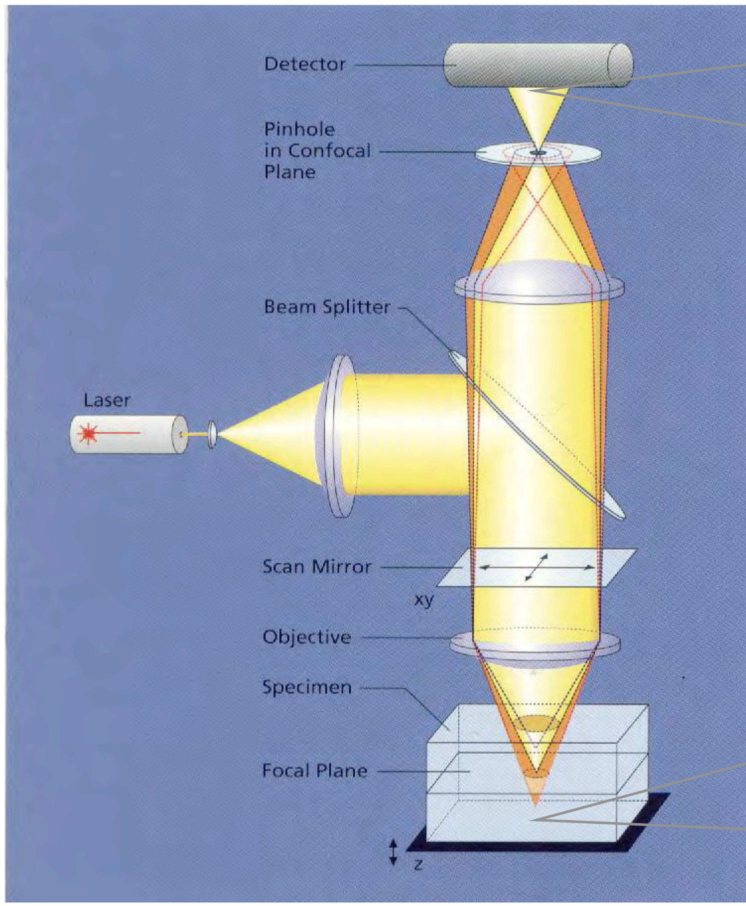
but, most CCDs and CMOS APS are saturated

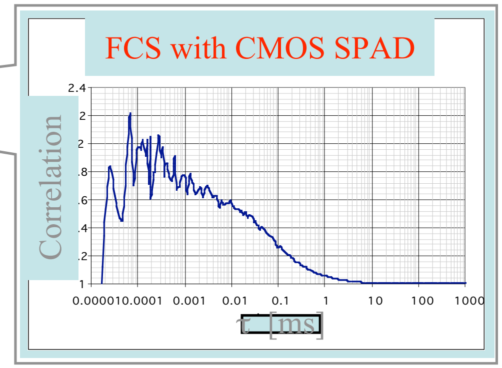


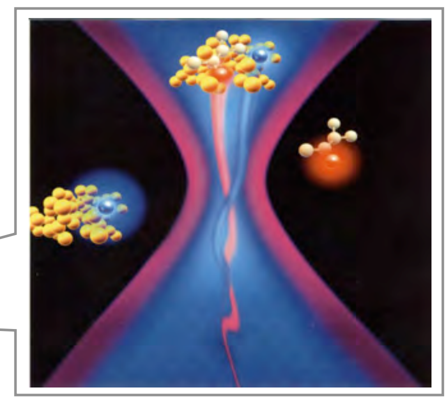
[Grinvald et al., 2001]

Fluorescence Correlation Spectroscopy

CTI project 5814.1



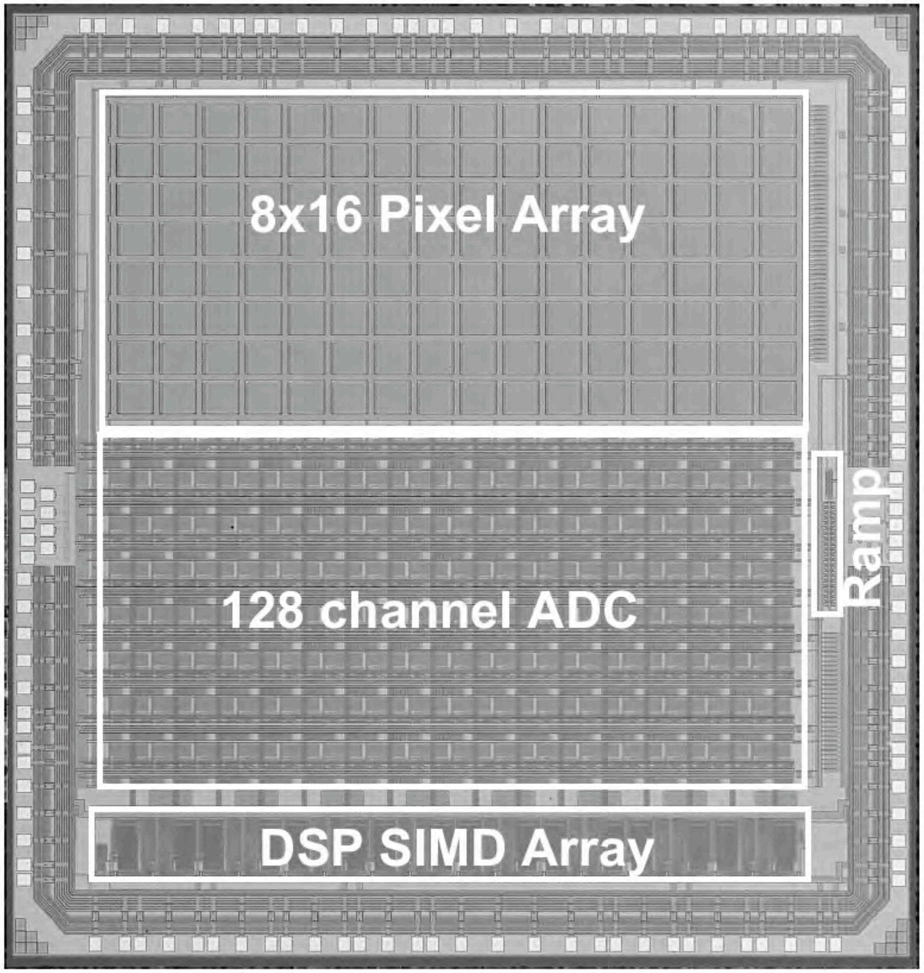




→*Picosecond time resolution* is needed to build sufficiently precise characterization

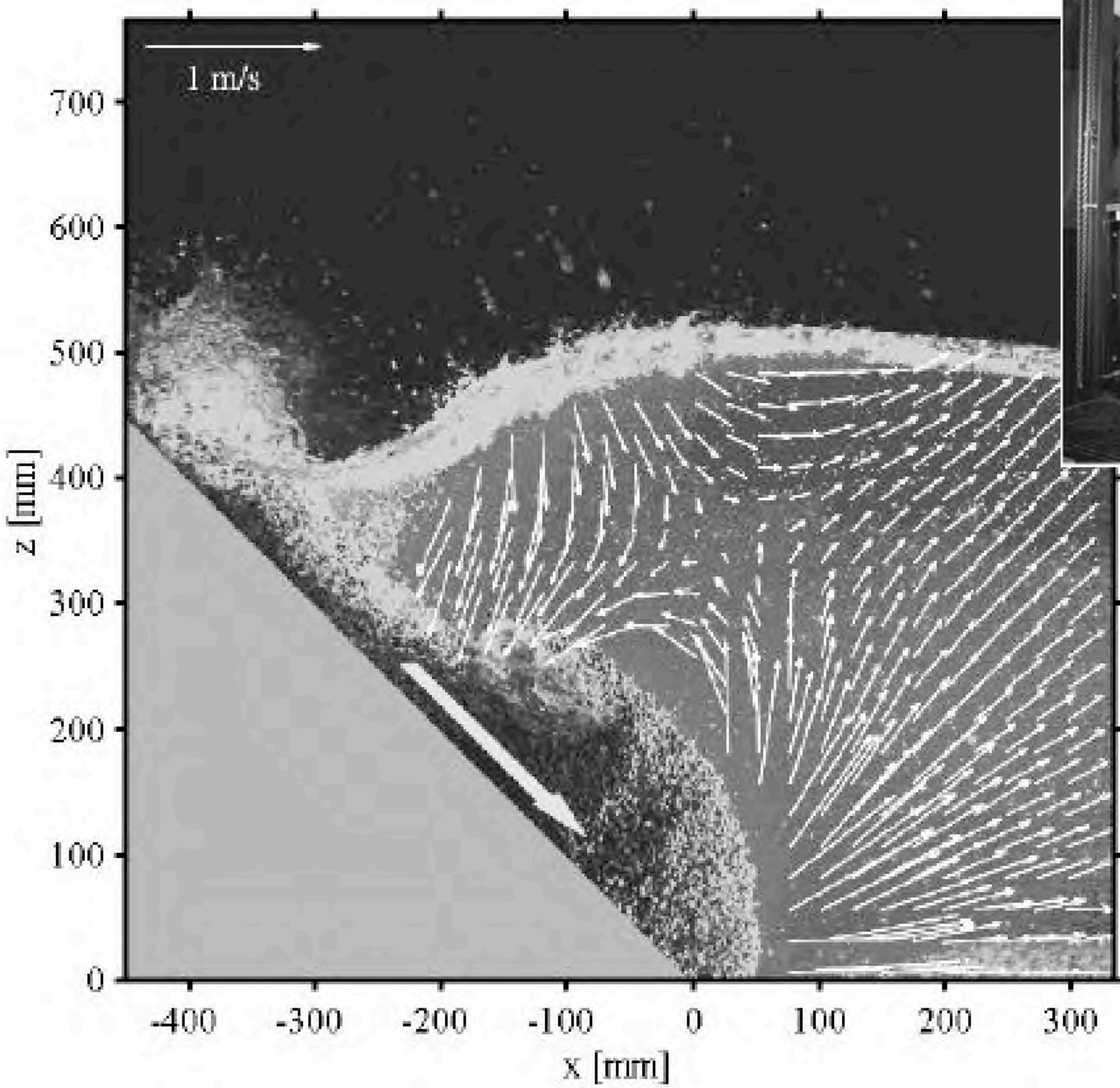
Bioluminescence Detection

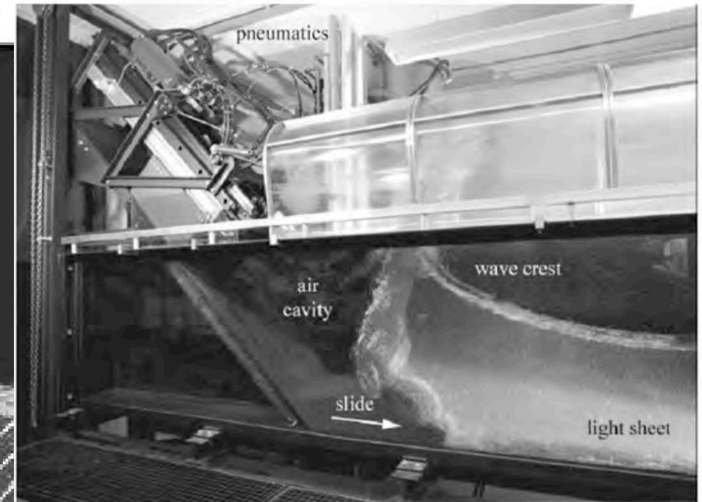
- Principle
  - Luciferase based assay methods (550nm) used to detect pathogens, proteins and DNA sequencing
- Features:
  - *Sensitivity: 10^{-6}Lx*
  - pixel size: 250x250um



[Eltoukhy et al., ISSCC 2004]

Fluid-dynamics Research





- Principle:
  - Particle image velocimetry (PIV)
- Features:
  - 1008x924 pixels
  - *Strobe illumination 1kHz*
  - Velocity profile computation via cross-correlation

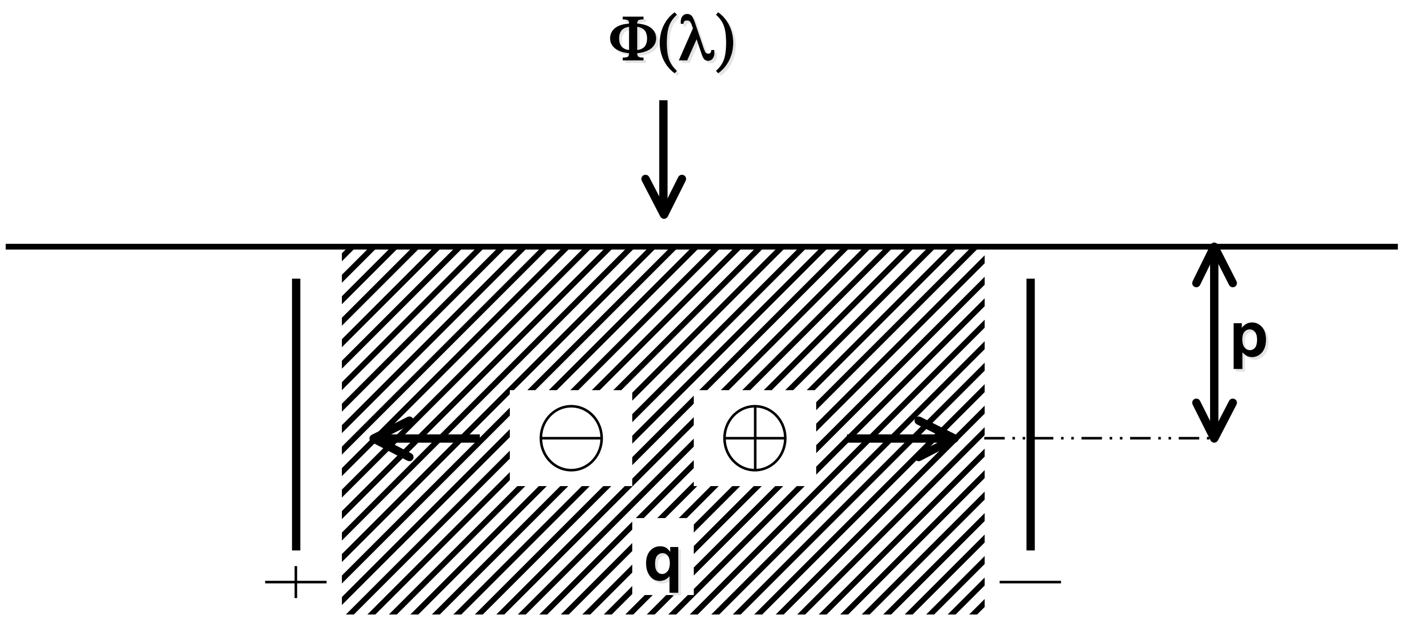
Courtesy of H.M.Fritz

Single Photon Projects

- Current
  - 3D camera
  - Near-saturation cortical imaging (EPFL-LS)
  - High-speed digital camera (Industry)
  - High-speed shutter digital camera (Columbia University)
- Near future
  - Ultra-high speed Calcium Flux in neurons (EPFL-LS)
  - 3D long-distance camera (Industry)
  - Free space com (Academia)
  - Transillumination (EPFL-MT)

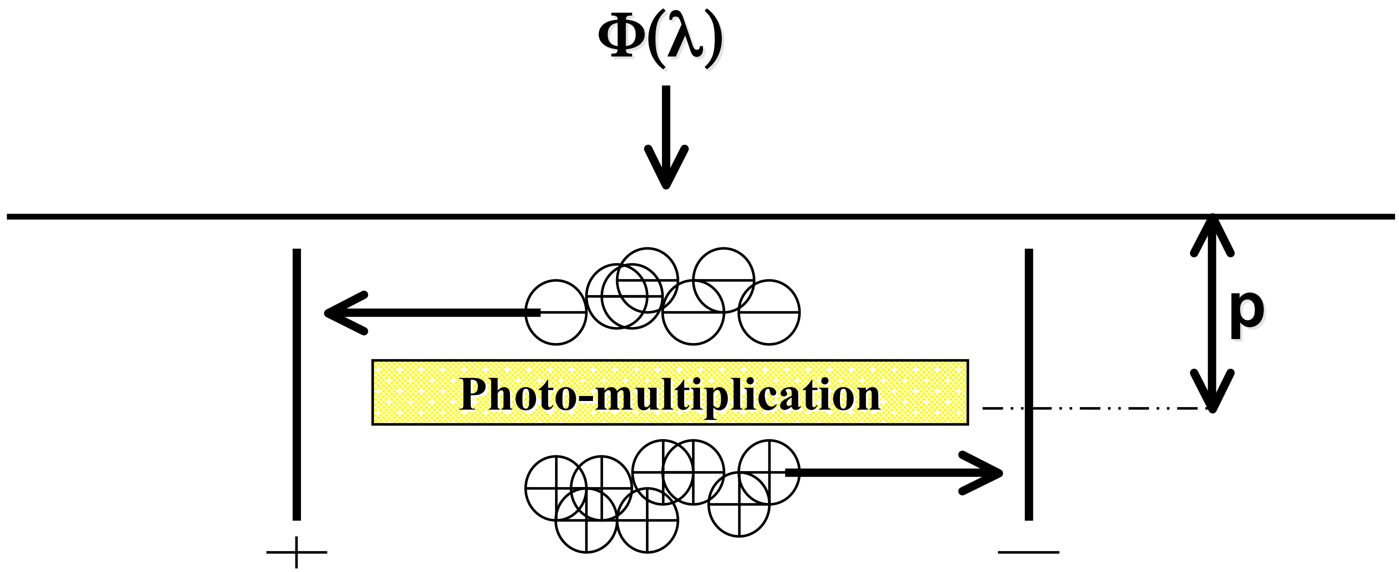
Single Photon Avalanche Diodes (SPADs)

Photoelectric Effect



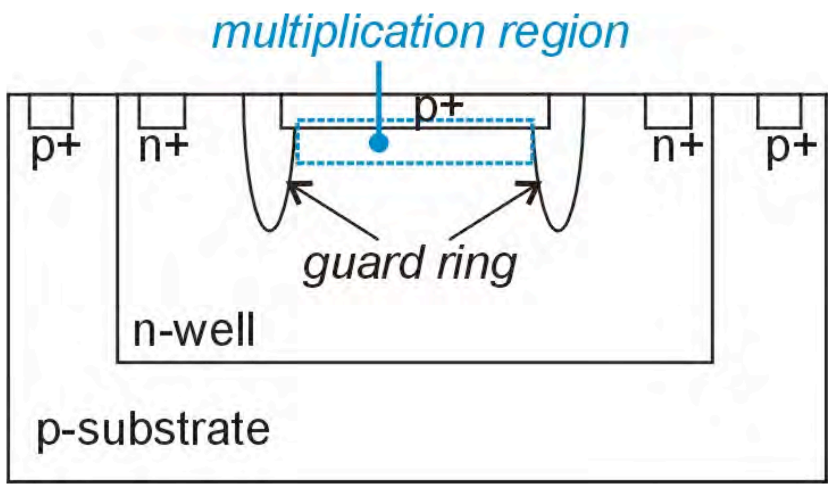
Parameters: QE, p, λ

Avalanche Effect



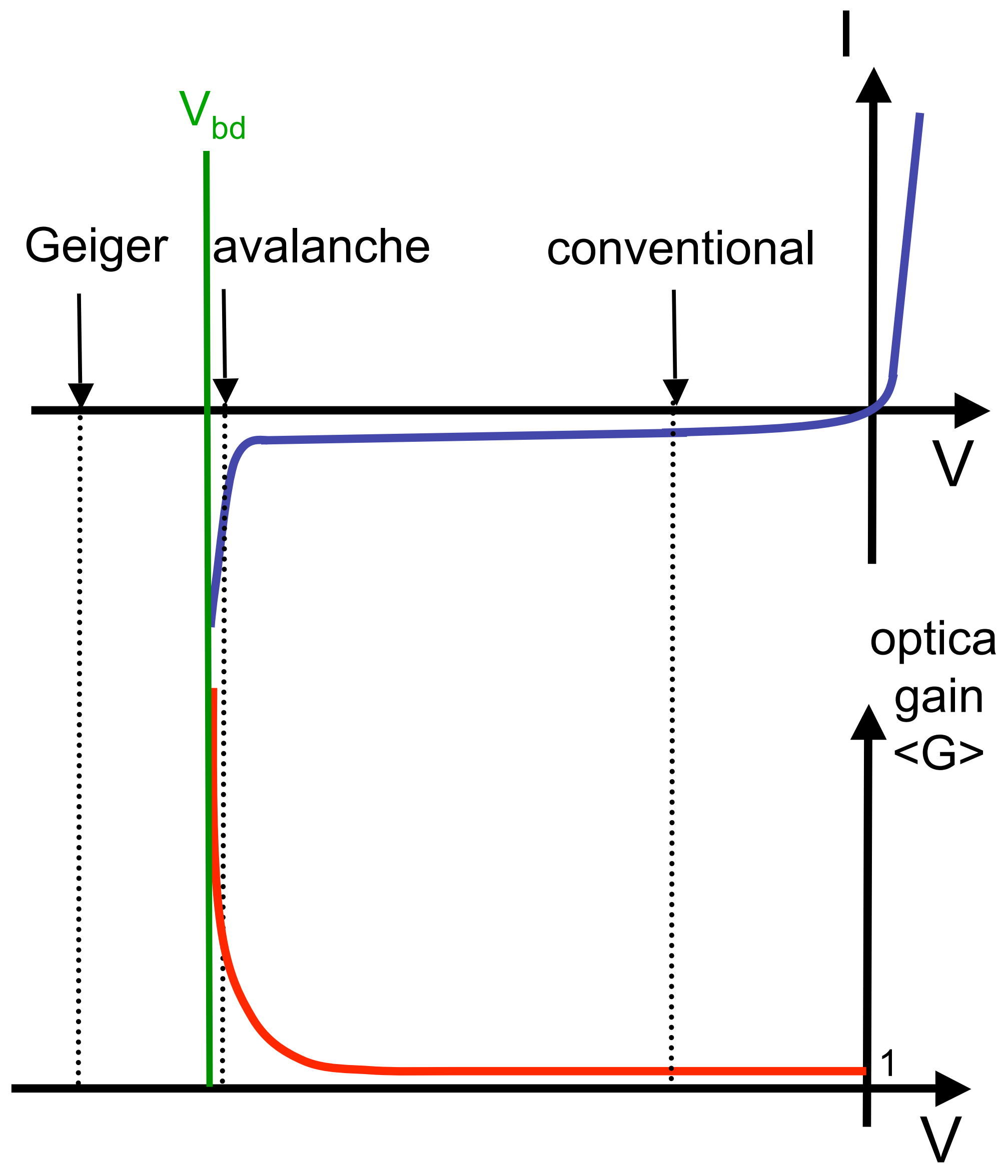
Parameters: QE, p, λ

SPAD Operating in Geiger Mode



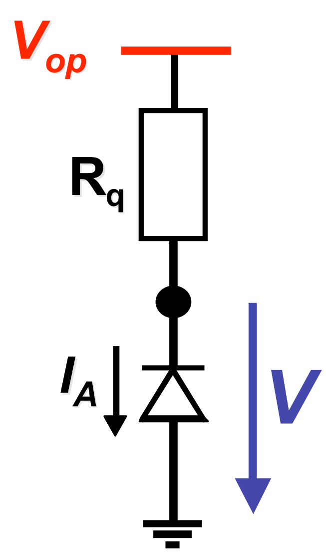
[Rochas, TransED, 2002]

- <u>In avalanche mode:</u>
  - <G> ≅ 1000
- <u>In Geiger mode:</u>
  - <G> → ∞
  - ➡ **avalanche must be stopped**

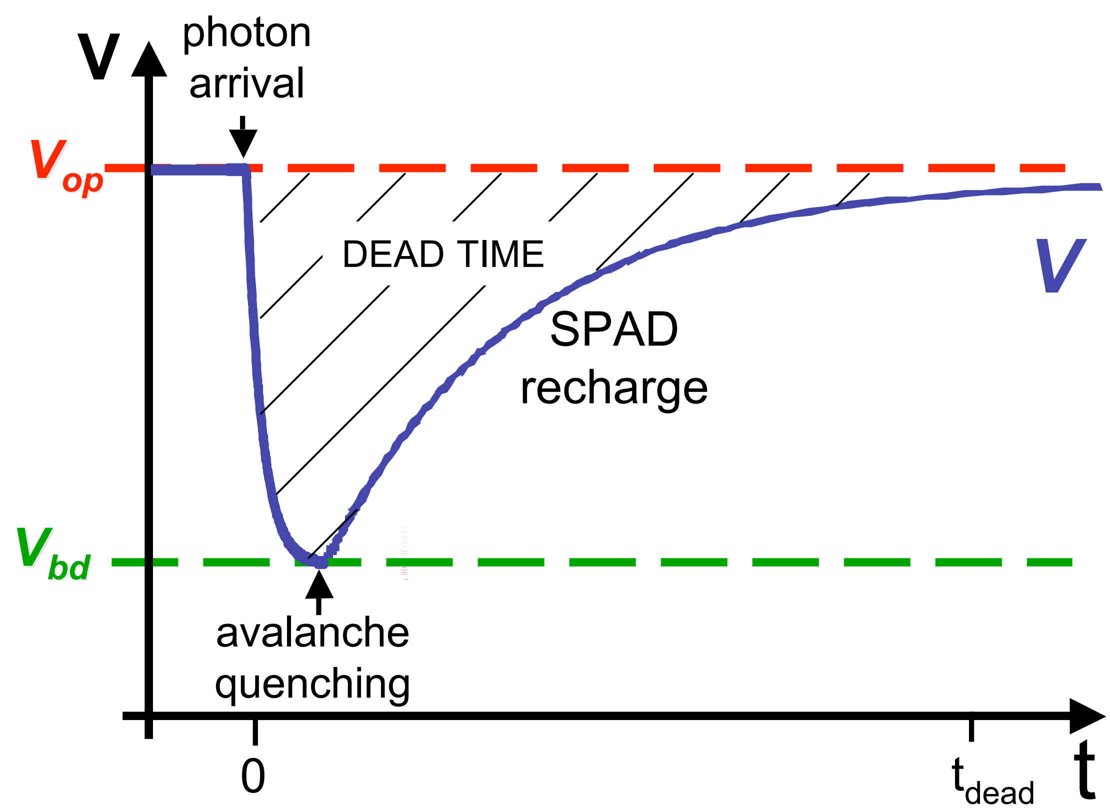


SPAD Operating in Geiger Mode

passive quenching:



operation cycle:



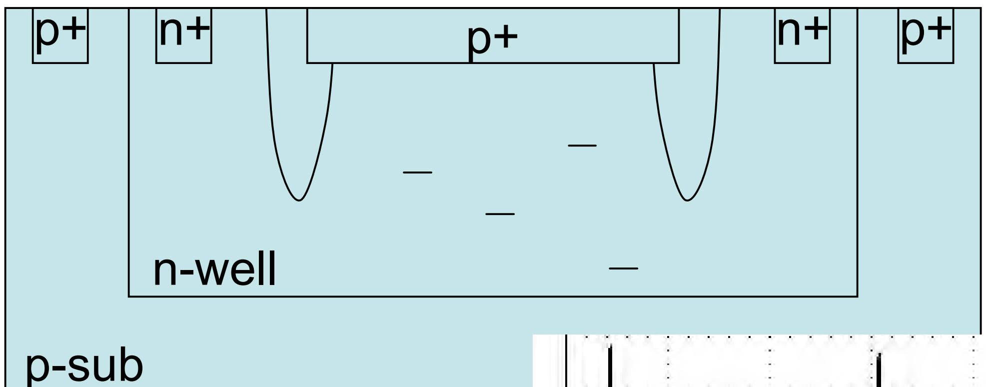
— One photon ➡ one cycle (dead time definition)

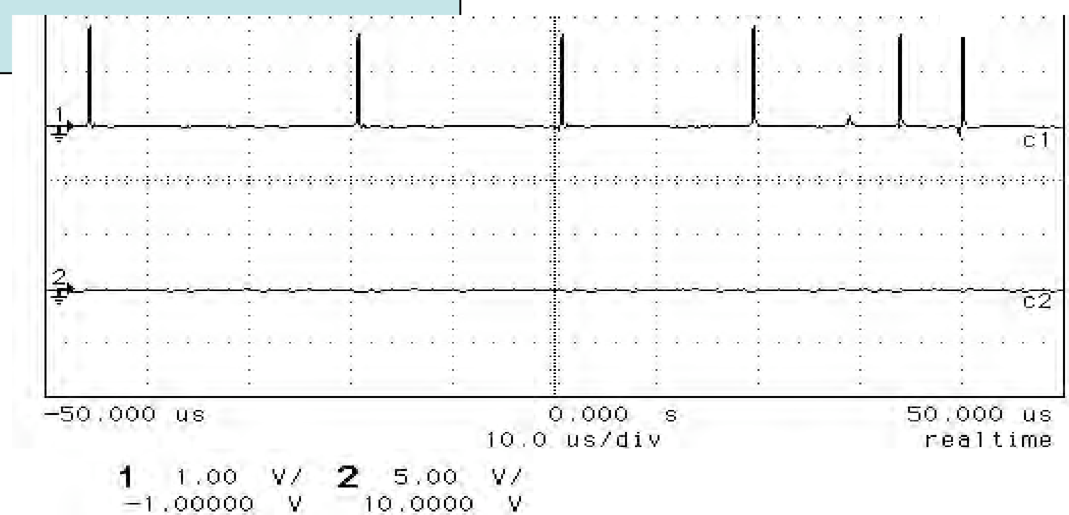
— Thermally generated carriers ➡ dark counts

Dark Counts

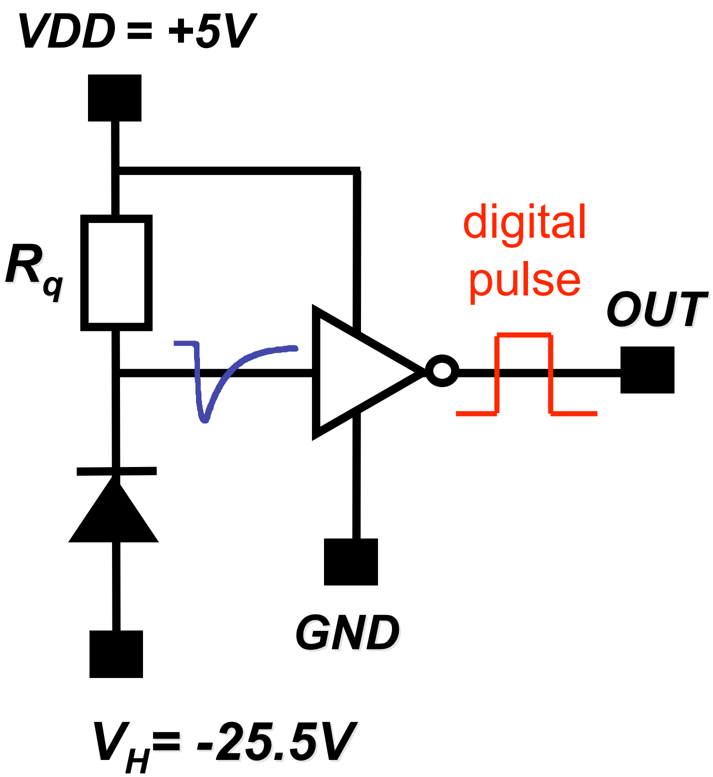
Intuition:

Traps capture photocharges and release them randomly (by diffusion, tunneling, etc.) → avalanche is triggered → spurious pulses

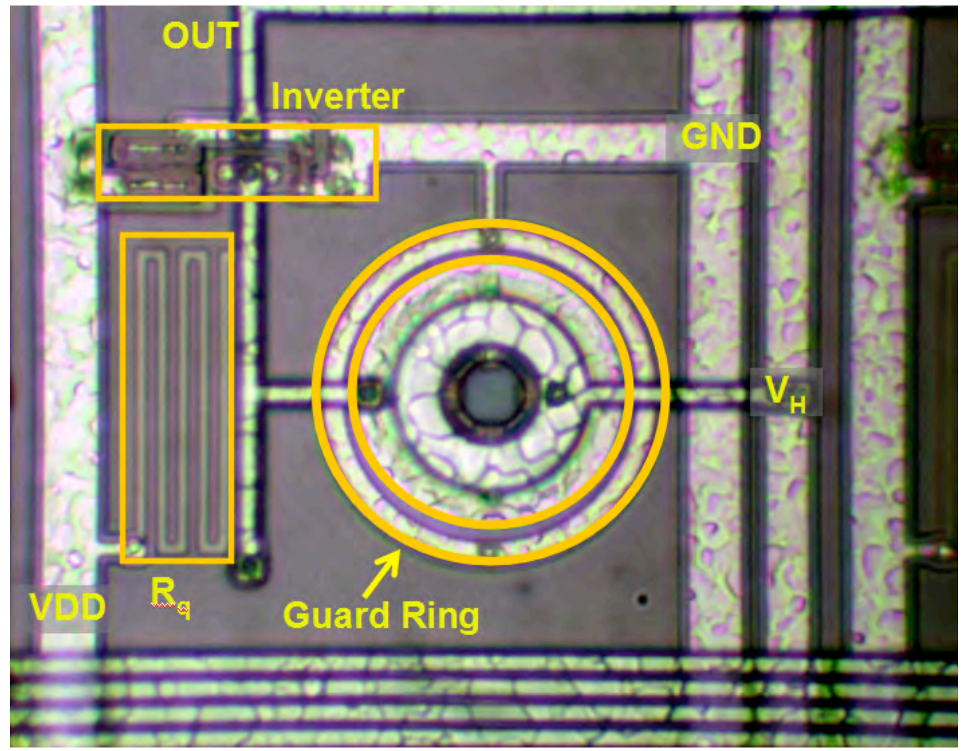




CMOS SPAD (ISSCC04)



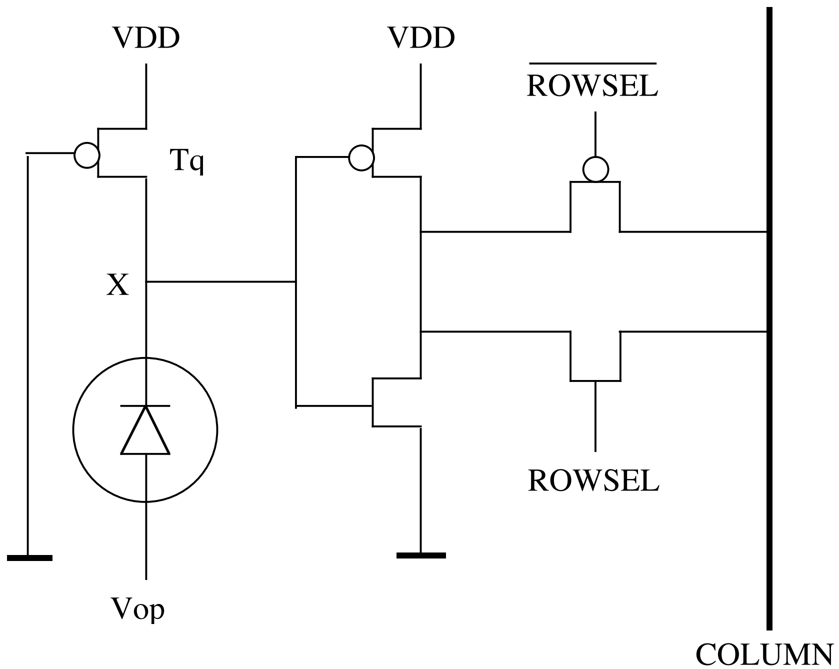
$V_{op} = VDD + |V_H| > V_{bd}$

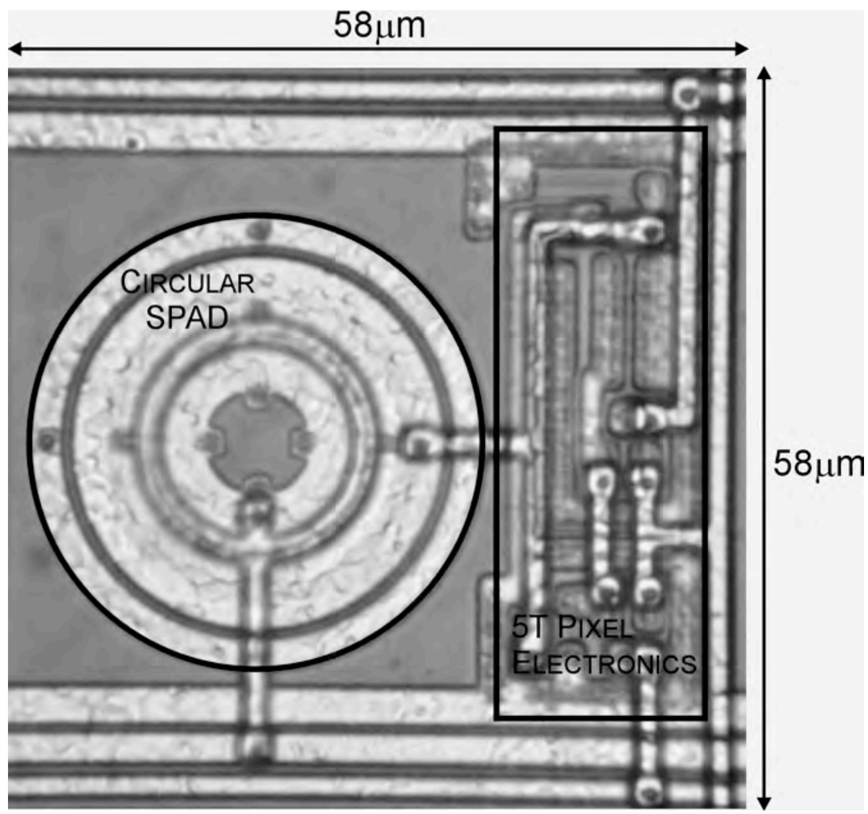


Main features of the pixel

- dead time : 32ns
- PDP: ~ 12% @ 635nm
- dark count rate typ. 350Hz
- timing jitter: < 50ps

SPAD Evolution (ISSCC05)





Features

- Pitch reduction
- Column routing mechanism
- MOS Quenching resistance

3D Imaging

Goal

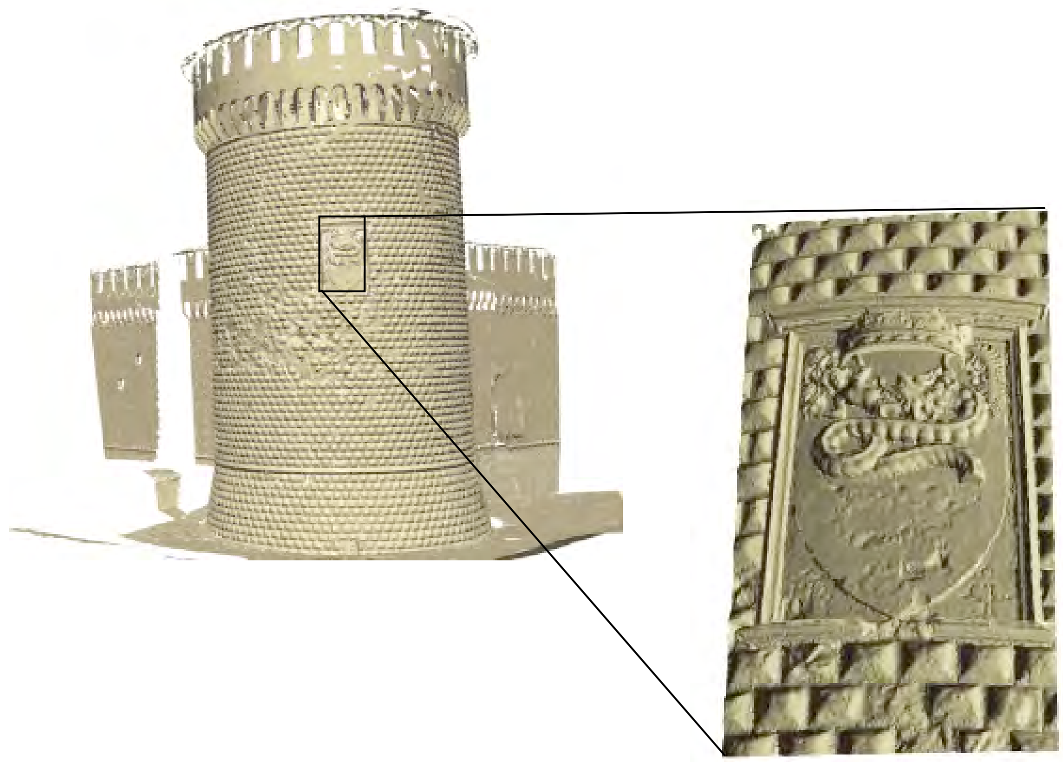
- Find distance to each point in the scene (*rangefinding*)
- Build depth map of the scene

Specific 3D Applications

- Surveying
  - Geo, construction
- Automotive
  - Airbag deployment
  - Collision detection/avoidance
- Security
  - facial recognition
  - room volumetric analysis
- Consumer
  - Human-computer interfaces
  - VR
- Medical/Research
  - Optical tomography
  - Bio-chemical & molecular analysis

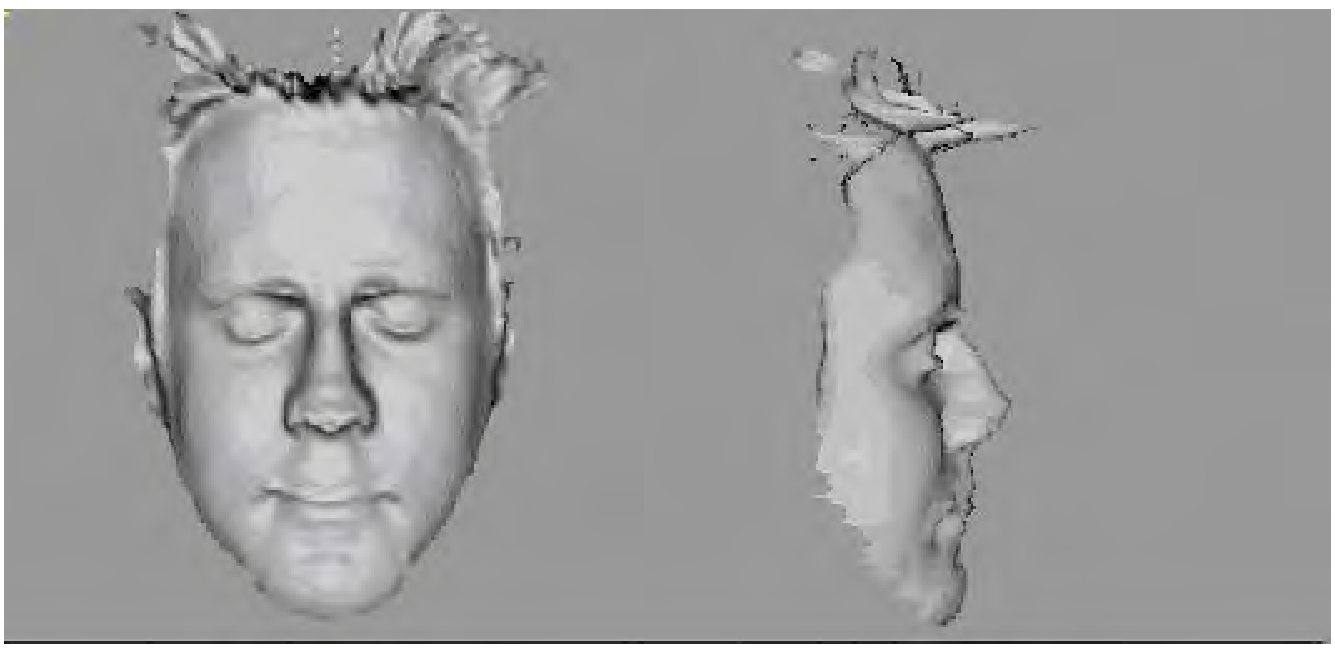
Electronic Theodolites

- Some specifications
  - Sub-mm precision
  - ~100m range
  - Low fps(?)



Face Recognition

- Some specifications
  - 600um~1mm precision
  - 1~2m range
  - 30 fps



Virtual (Planar) Keyboard

- Some specifications
  - 2mm precision
  - 20~30cm range
  - 50-70 fps

3D Imaging:

optical Time-of-flight (TOF)

Rangefinding

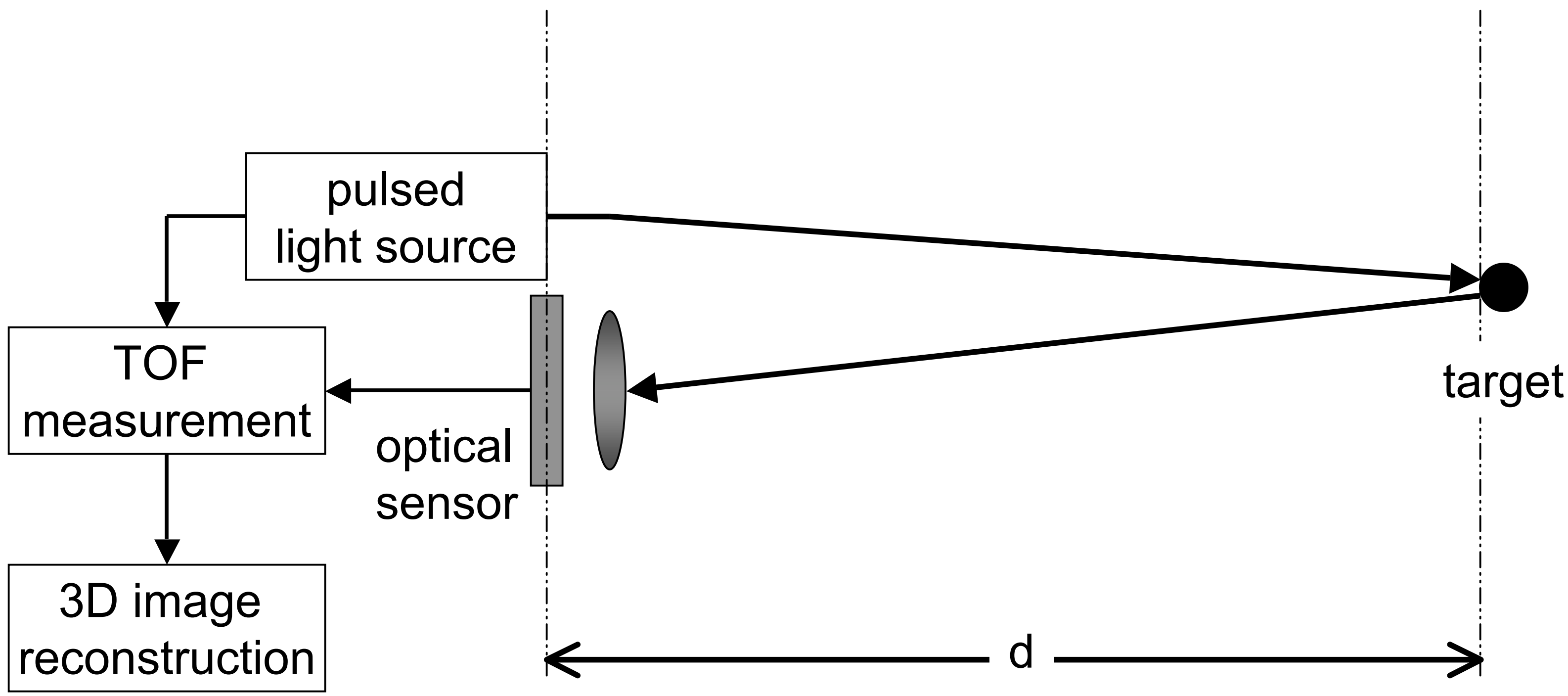
Methods

- Interferometry
- Triangulation
- **Time-of-flight (TOF)**

Principle

- **Light**
- RF
- Ultrasound
- Magnetism

Optical TOF Based Rangefinding



d = (c/2) TOF

Conventional Approaches

- **Single** highly sensitive detector with mechanical scanning device
- *Problems*:
  - → high-cost
  - → non-portable

- **Array** of conventional CMOS detectors with high-power optical source
- *Problems*:
  - → 10~100W peak power
  - → potentially unsafe

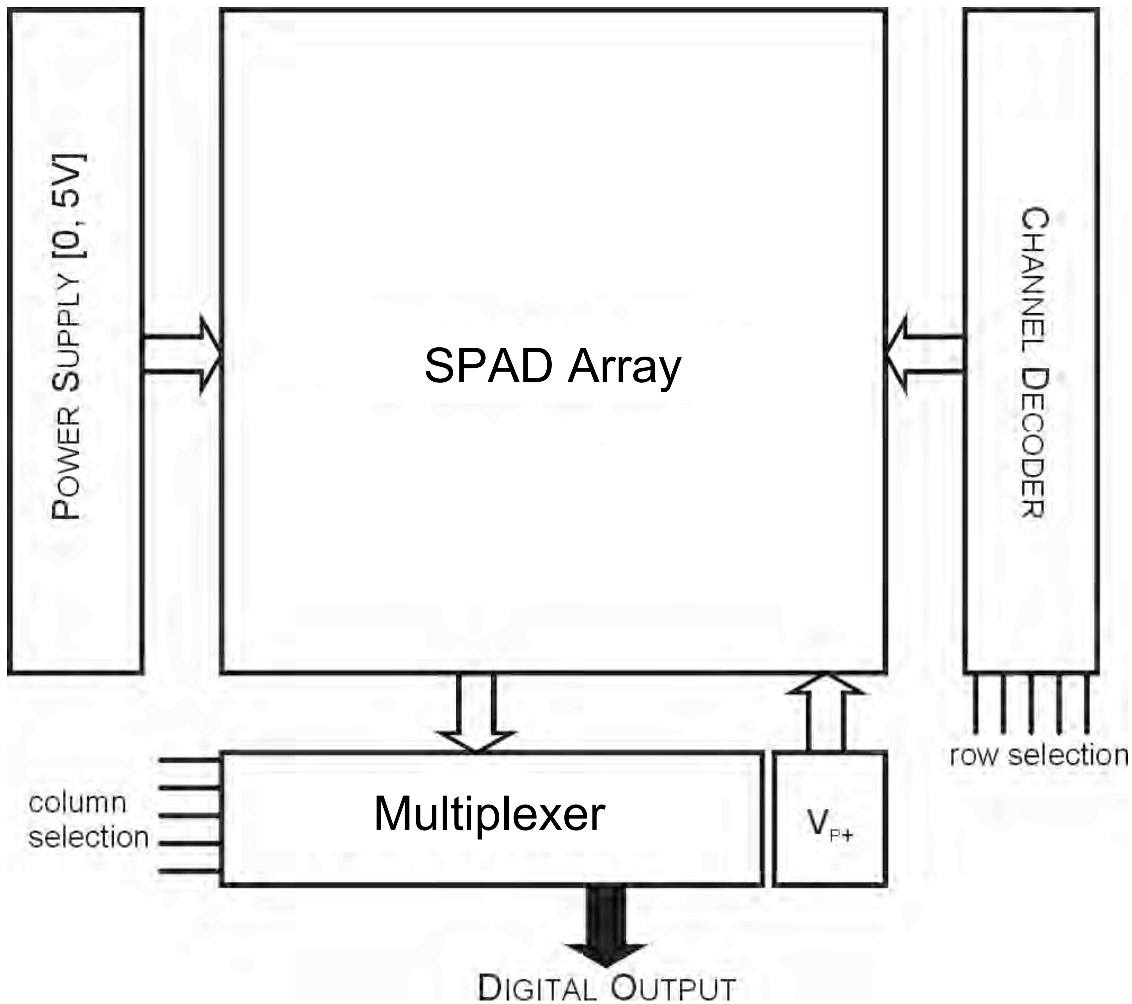
Our Approach

- **Array** of Single Photon Avalanche Diodes (SPADs) fabricated in CMOS process
- *Pros*:
  - Milliwatt laser source (peak power)
  - Compact
  - Low cost

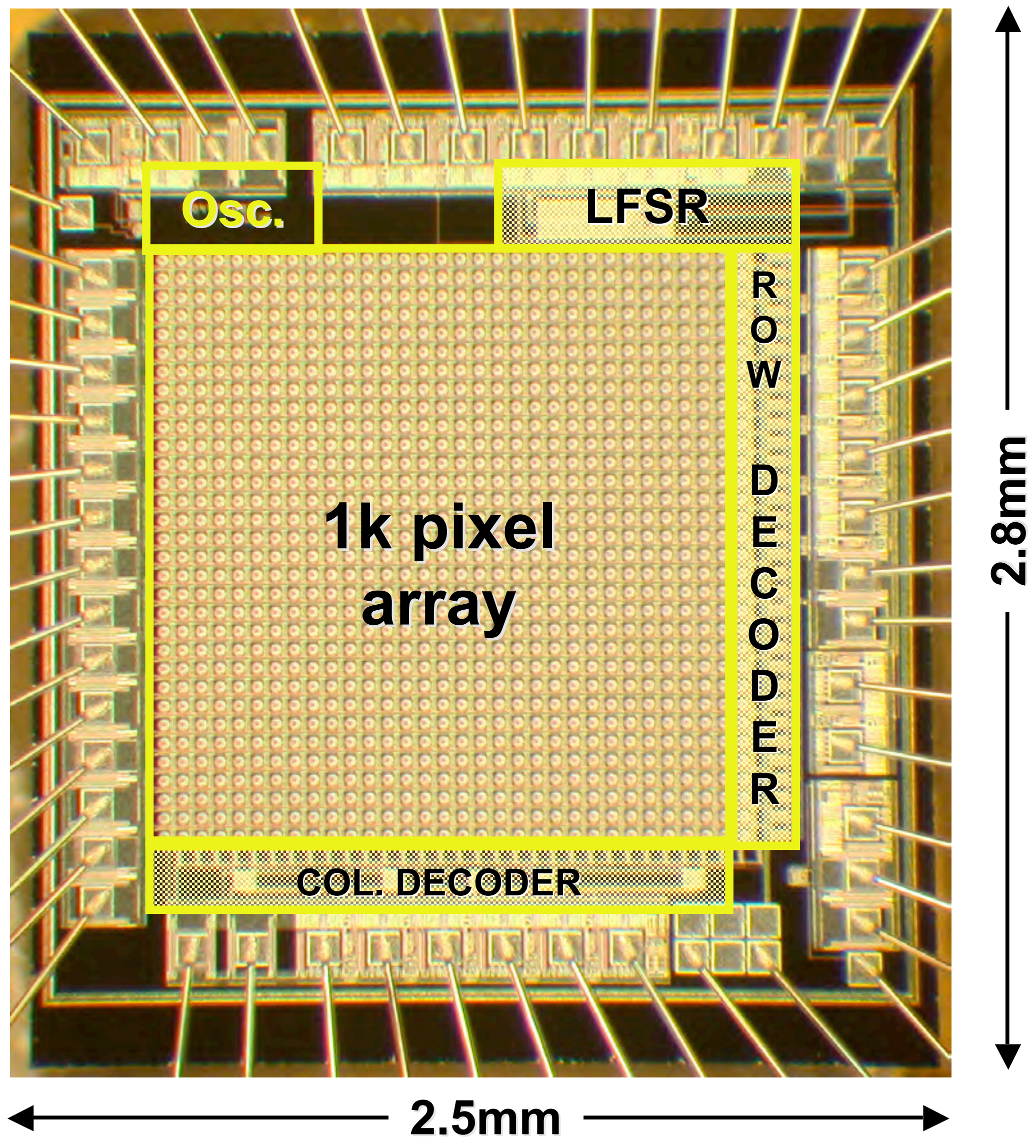
3D Imaging:

System Architecture

Sensor Architecture

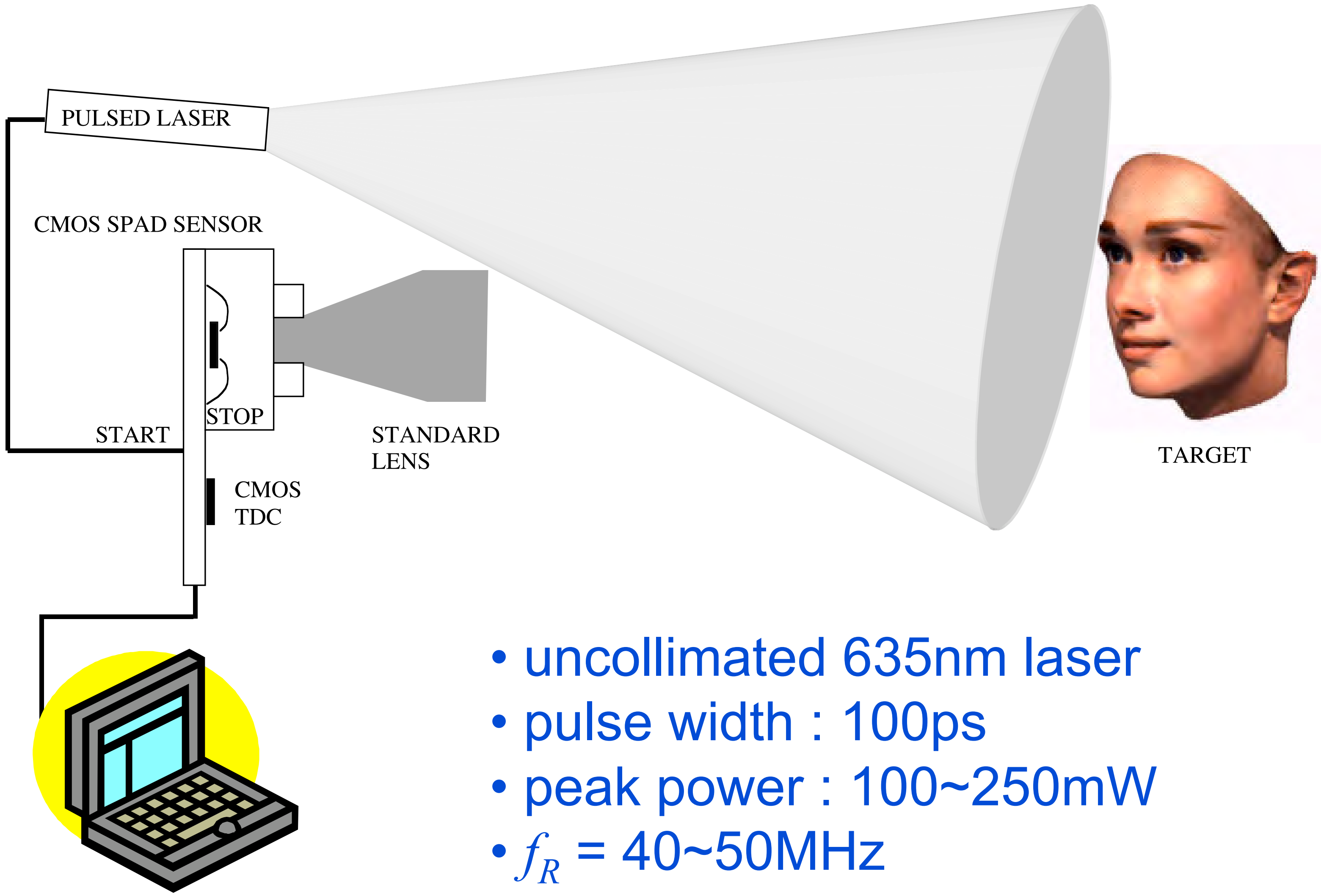


Sensor Photomicrograph



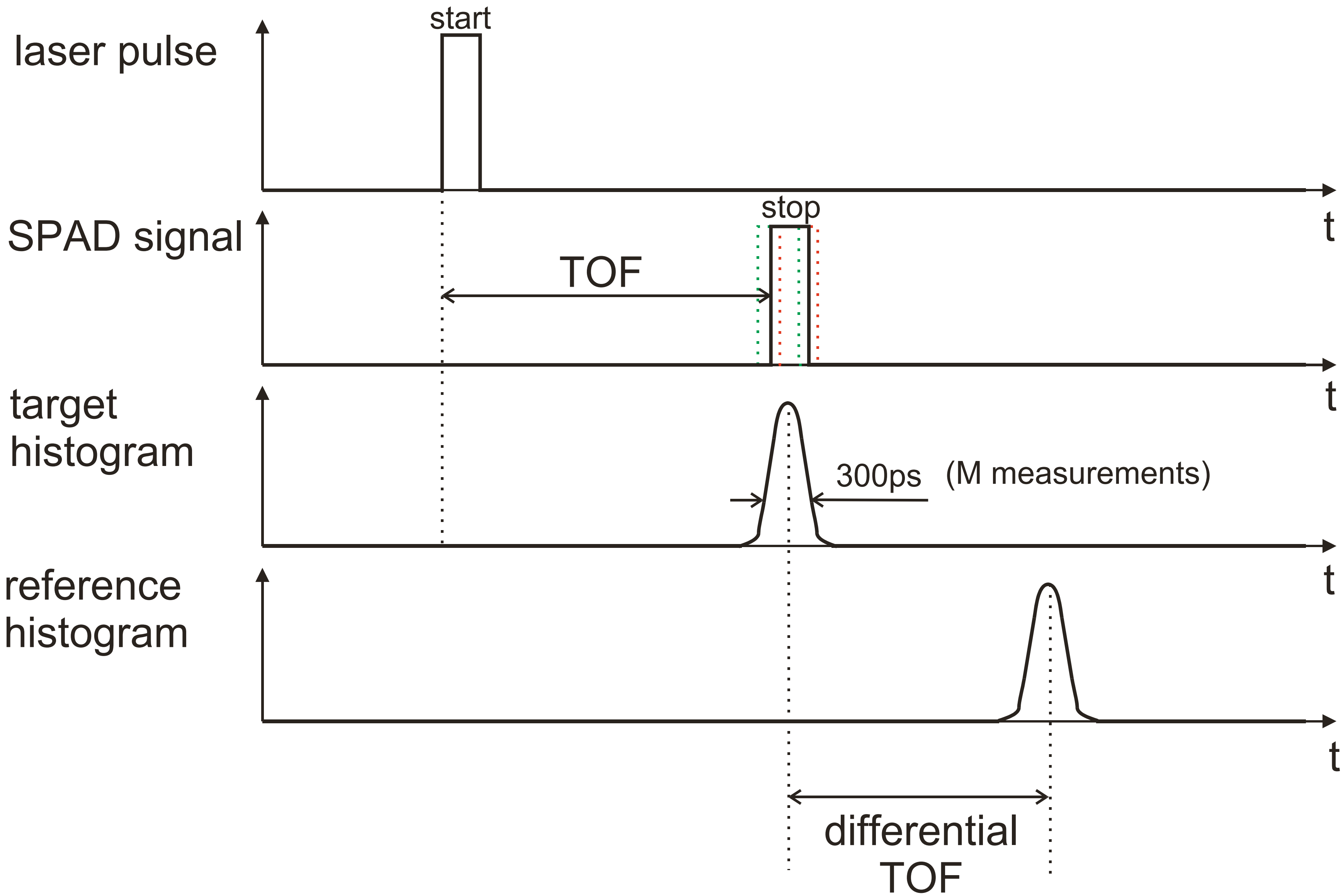
0.8um CMOS technology

Electro-Optical System



- uncollimated 635nm laser
- pulse width : 100ps
- peak power : 100~250mW
- f_R = 40~50MHz

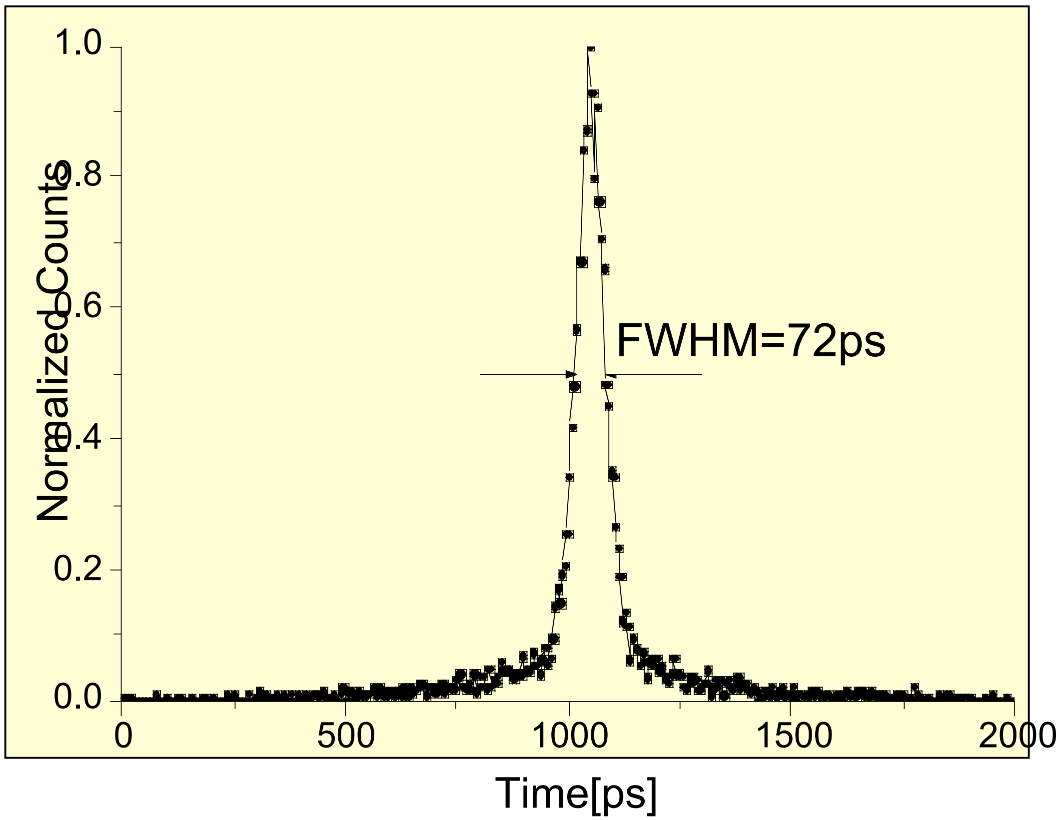
TOF Computing

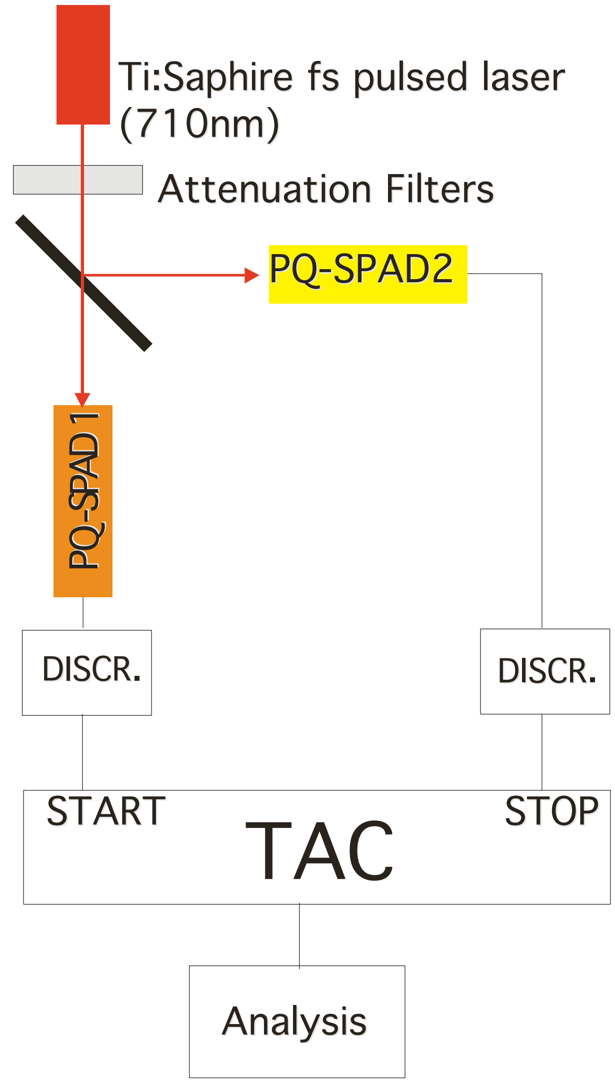


3D Imaging:

Measurements

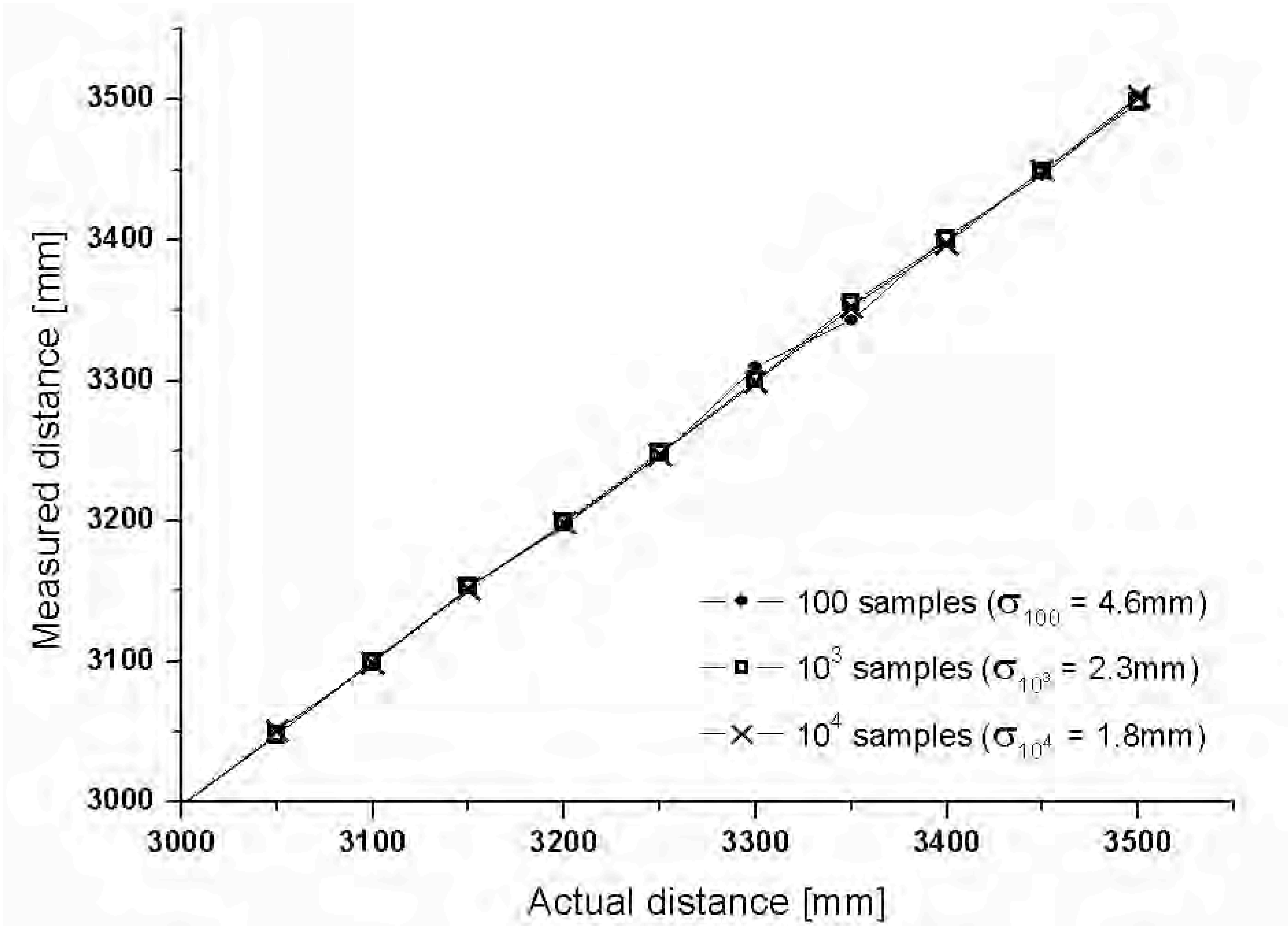
Time Resolution





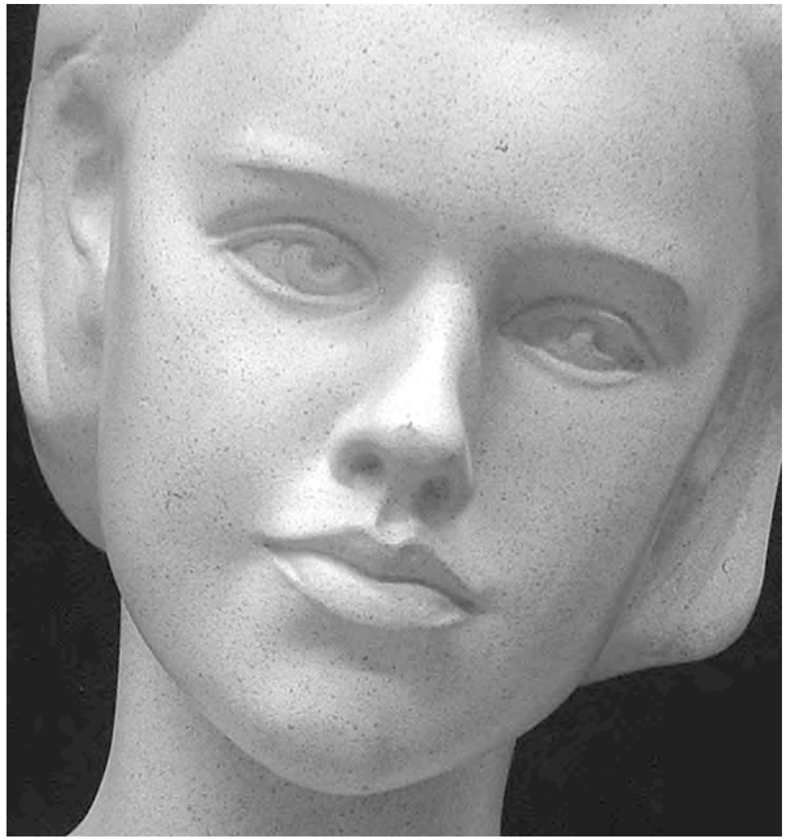
PQ-SPAD Timing Resolution: 50ps

Distance



Measured distance [mm]
3000
3100
3200
3300
3400
3500
Actual distance [mm]
100 samples (σ_{100} = 4.6mm)
10^3 samples (σ_{10^3} = 2.3mm)
10^4 samples (σ_{10^4} = 1.8mm)

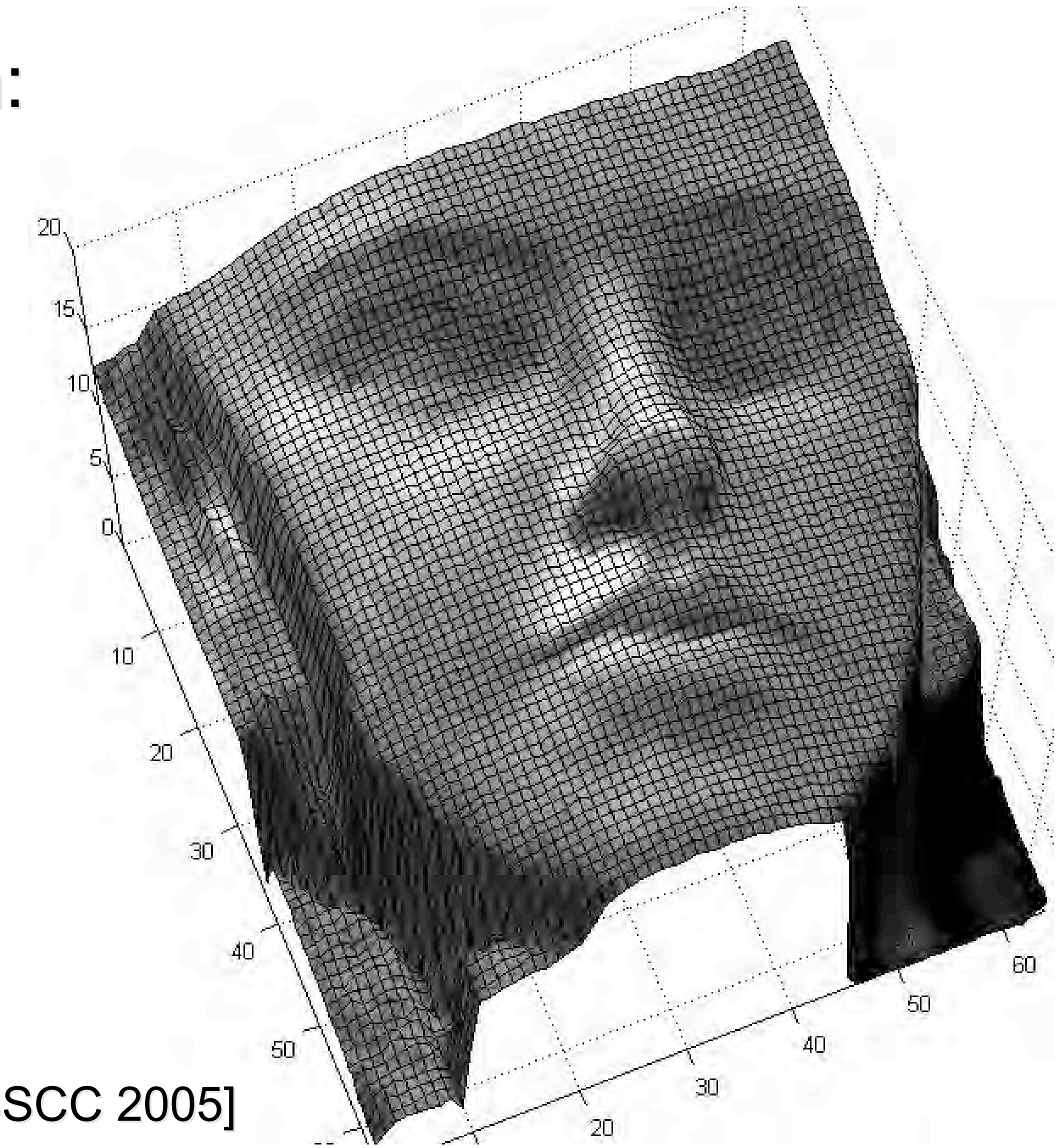
Model



High resolution Camera:
20cm x 20cm view

Depth Map Example

- Lateral resolution:
  - 64x64 pixels
- Depth resolution:
  - 1.3mm (wc)
- Range:
  - 3.75m



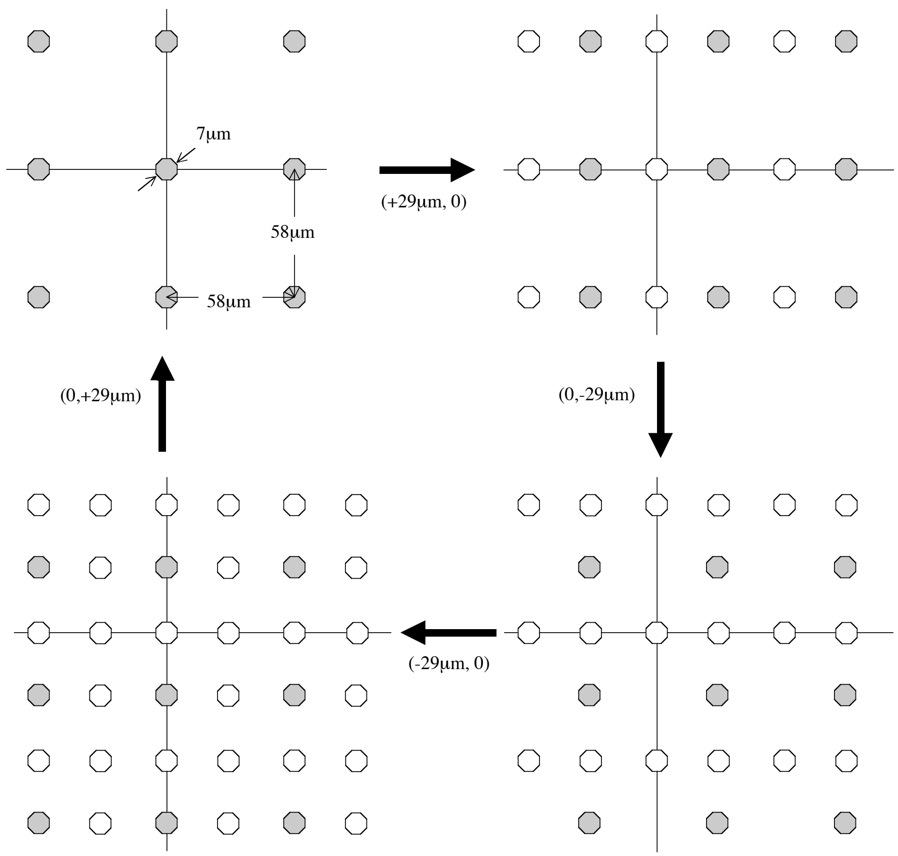
[Niclass and Charbon, ISSCC 2005]

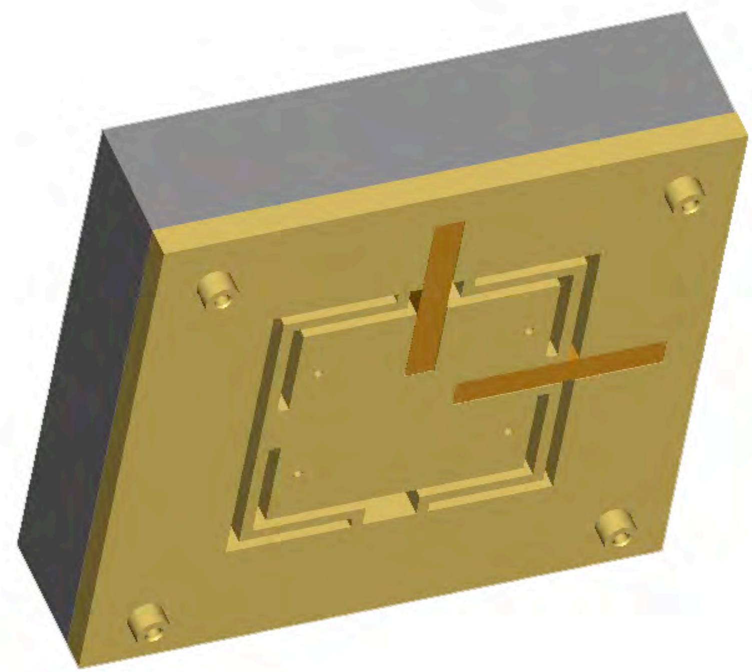
Companion Techniques

- Multi-exposure super-resolution techniques
  - Microscanning (x-/y- piezo elements)
  - S/R algorithm (LCAV, Prof. Vetterli)

- CMOS time-to-digital-converter (TDC) Integration
  - Current resolution: 100ps (0.8μm)
  - Target (under test): 25ps (0.18μm)

Microscanning Mechanism





CMOS Time-to-Digital-Converter

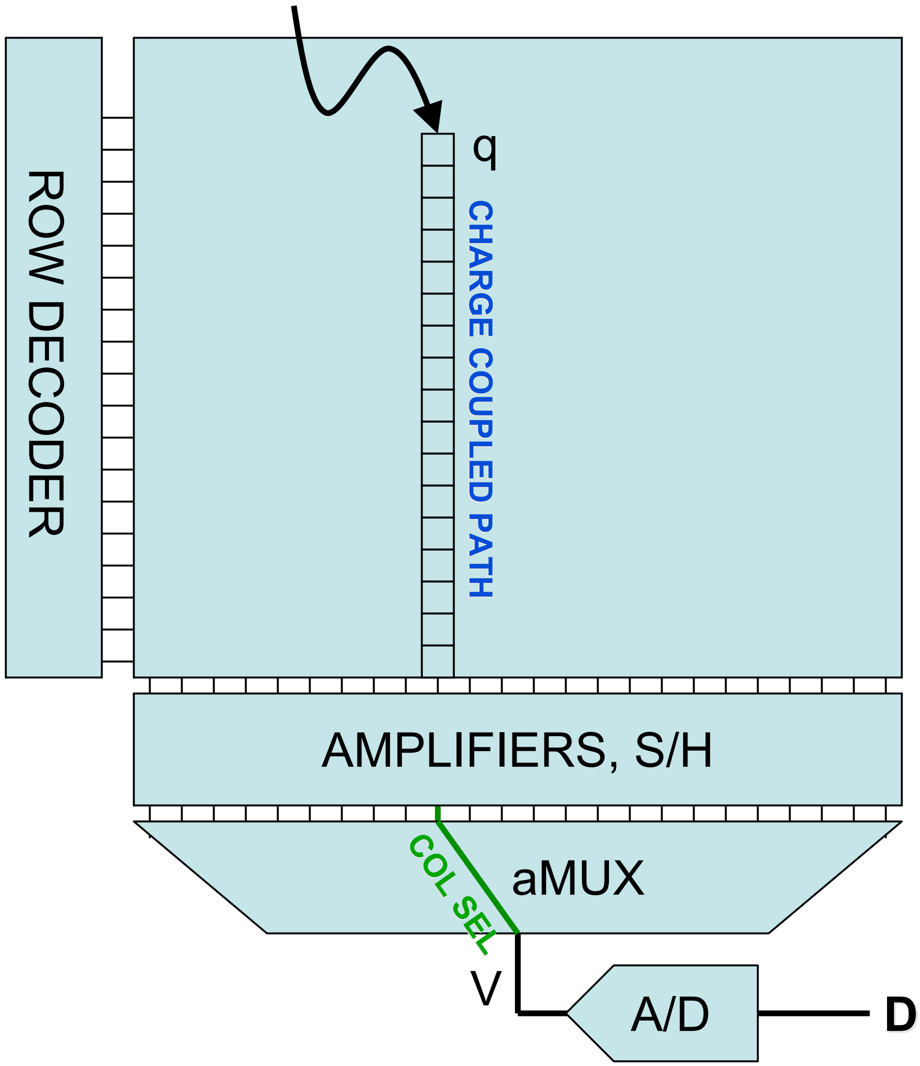
- CMOS TDC (RSUT)
- Resolution: 100ps
- Accuracy: <30ps
- Clock: 40MHz

3D Performance Summary

Parameter	**32x32**	**64x64**
W.C. axial uncertainty σ(d) (10k meas.)	1.8mm	1.3mm
Axial range	0.15 ~ 4m	0.15 ~ 3.75m
Single measurement uncertainty σ(τ)	268ps	350ps
Opt. peak/average power	100mW/0.5mW	250mW/0.7mW
Repetition rate	50MHz	40MHz
Light pulse width	100ps	100ps
Chip power dissipation	<1mW	< 6mW

2D Imaging

CCDs (e.g.)



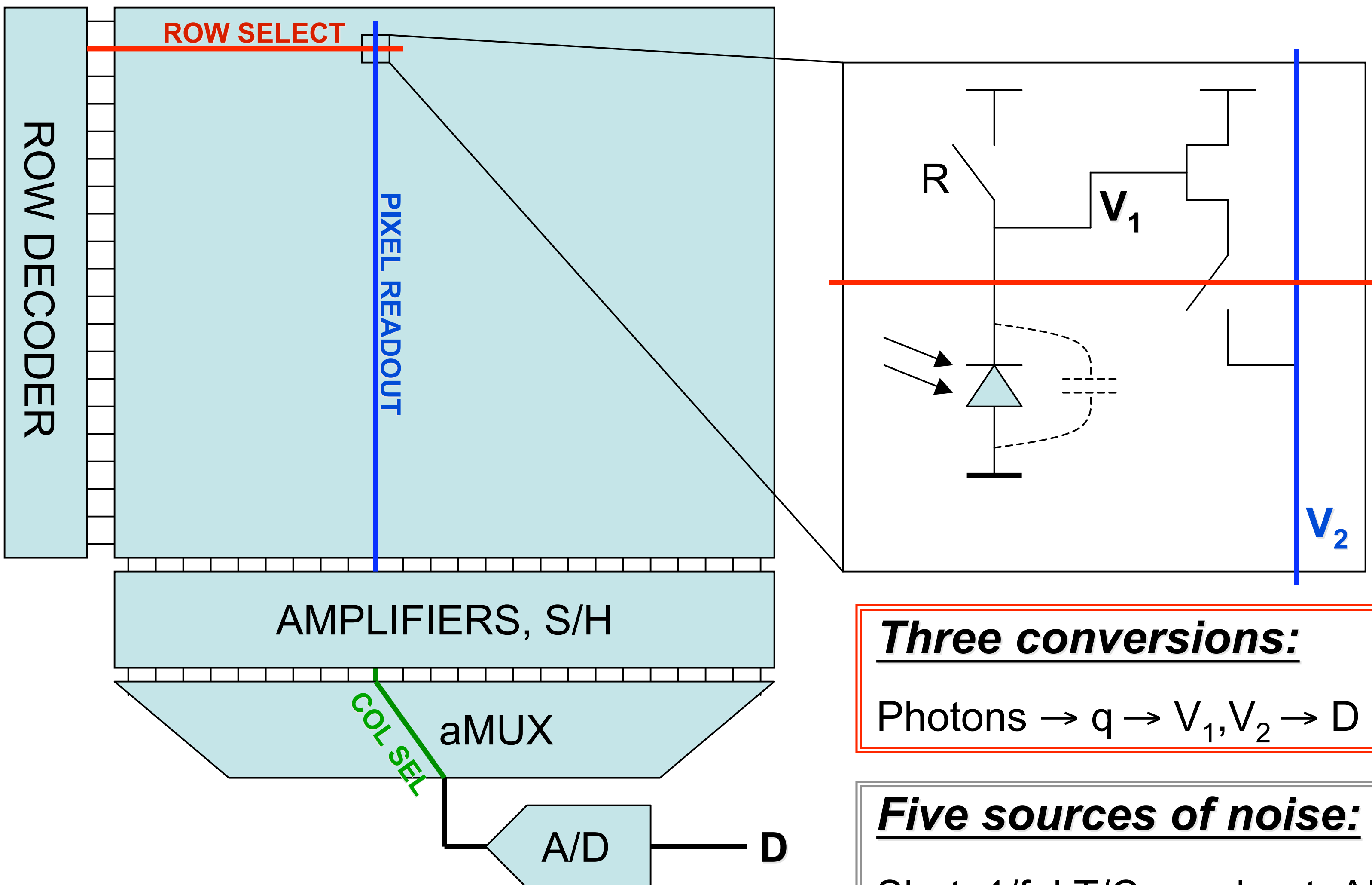
Three conversions:

Photons → q → V → D

Five sources of noise:

Shot, 1/f, kT/C, read-out, ADC

Conventional CMOS APS (e.g.)



Three conversions:

Photons → q → V_1,V_2 → D

Five sources of noise:

Shot, 1/f, kT/C, read-out, ADC

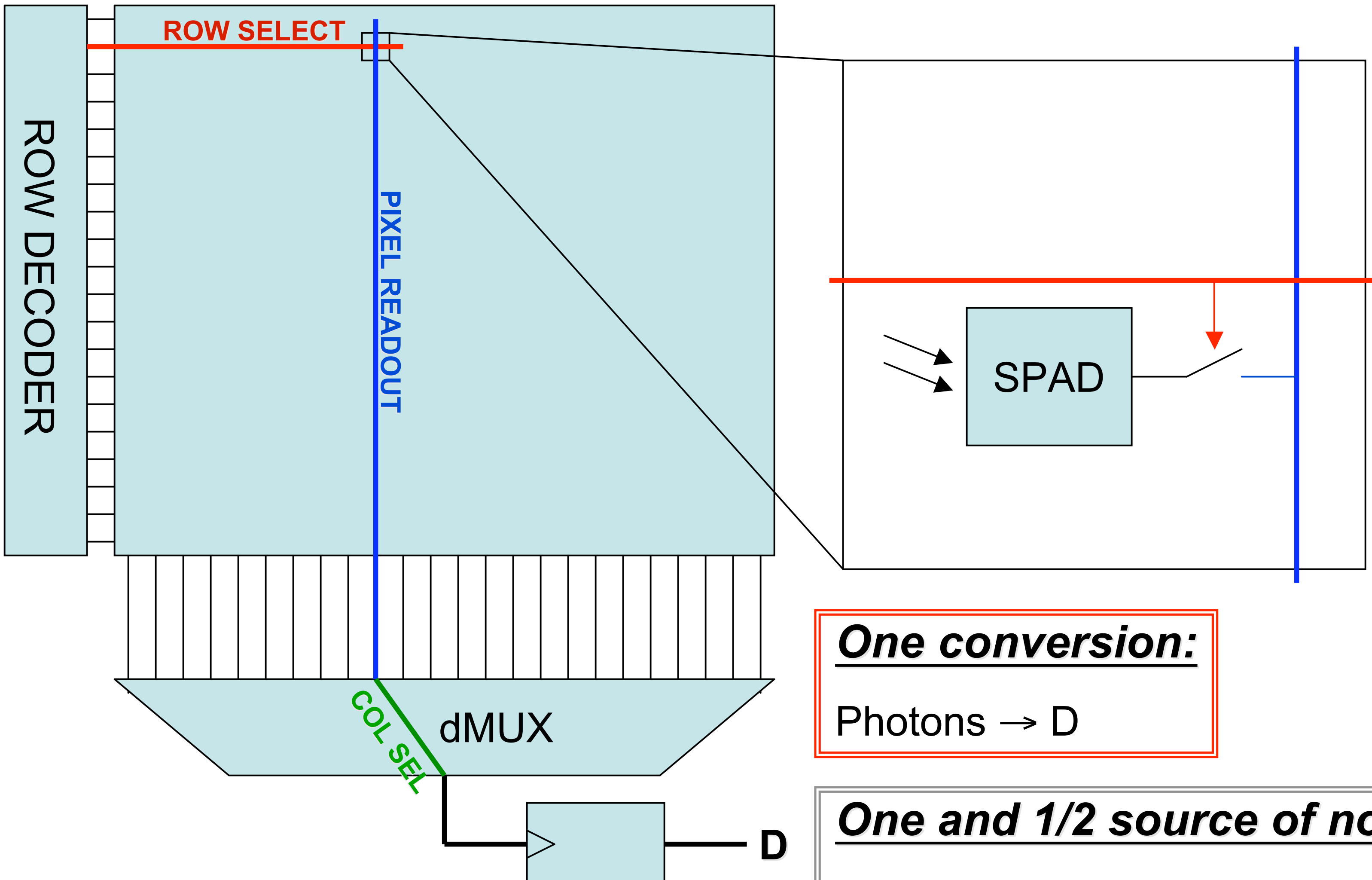
Performance of Interest

- Dynamic range
  - Ratio between the smallest detectable and maximum detectable intensity
- SNR
  - Ratio between signal due to intensity and noise
- FPS
  - Frames-per-second
- Pitch
  - Distance between pixels
- … and FPN, smearing, blooming, color, etc.

Limiting Factors

- Miminum # detectable photons
- Noise
  - Read-out noise
  - kT/C noise
  - 1/f noise
- Saturation
  - Limited number of available charges
- Speed (10kfps)

Imagers Based on SPADs



One conversion:

Photons → D

One and 1/2 source of noise:

Shot, DCR, (digital noise)

SPAD Arch Limiting Factors

- Miminum # detectable photons
  - Limited by DCR
- Noise
  - ~~Read-out noise~~
  - ~~kT/C noise~~
  - ~~1/f noise~~
- Saturation
  - Limited by dead time and read-out bandwidth
- Speed
  - Shown 250kpps

New Challenges

Departure from amplitude based imager

➡ Therefore:

- Local evaluation of intensity
- Intensity storage
- Digital noise
- Low-power operation

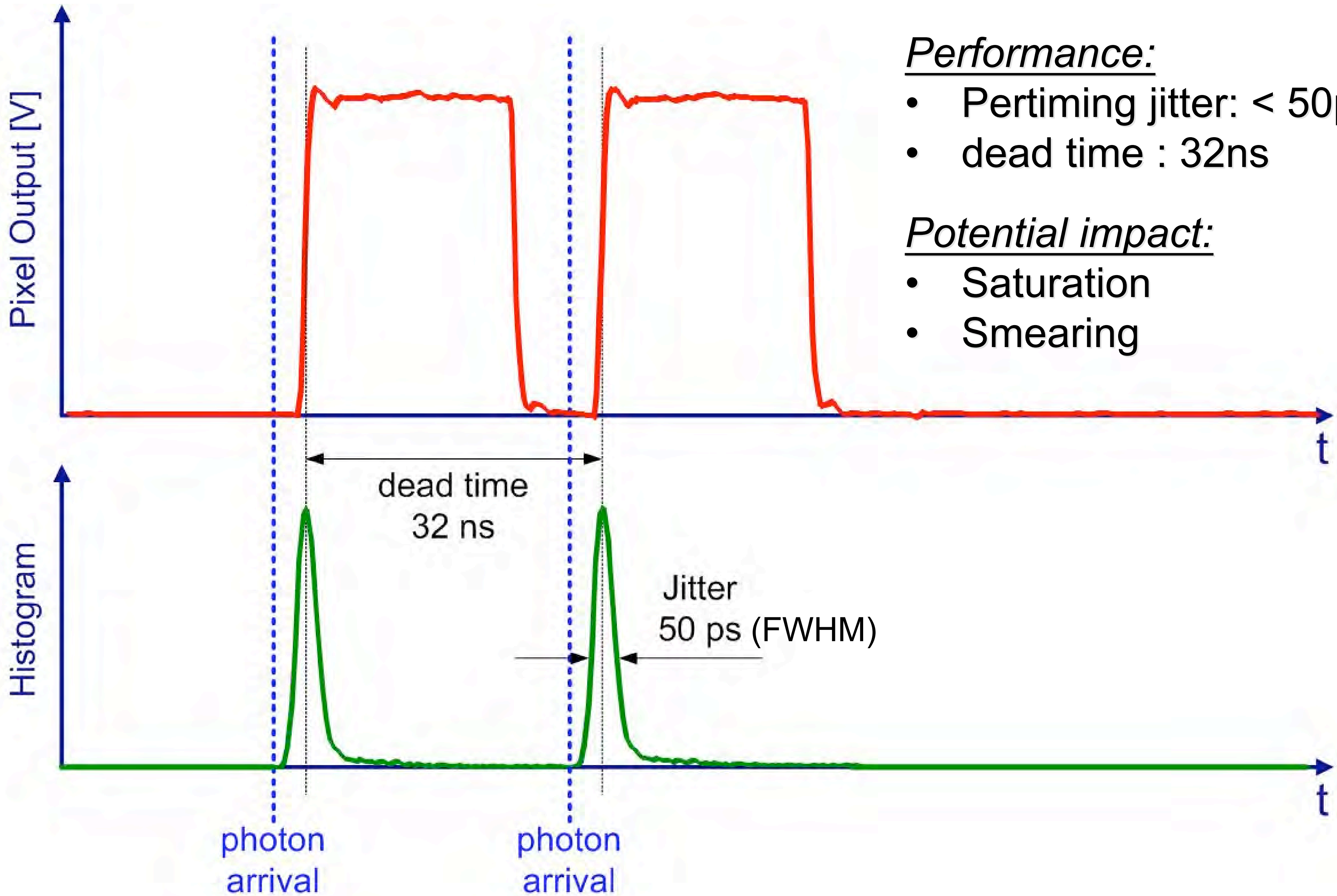
Example:

- R rows
- share column of bandwidth $B \leq 1/t_D$

Then, in average every pixel has B/R bandwidth, thus dynamic range $\approx 20\{Log(B/R)-Log(DCR)\}$

➡ Architecture directly influences Performance

Importance of Pixel Timing



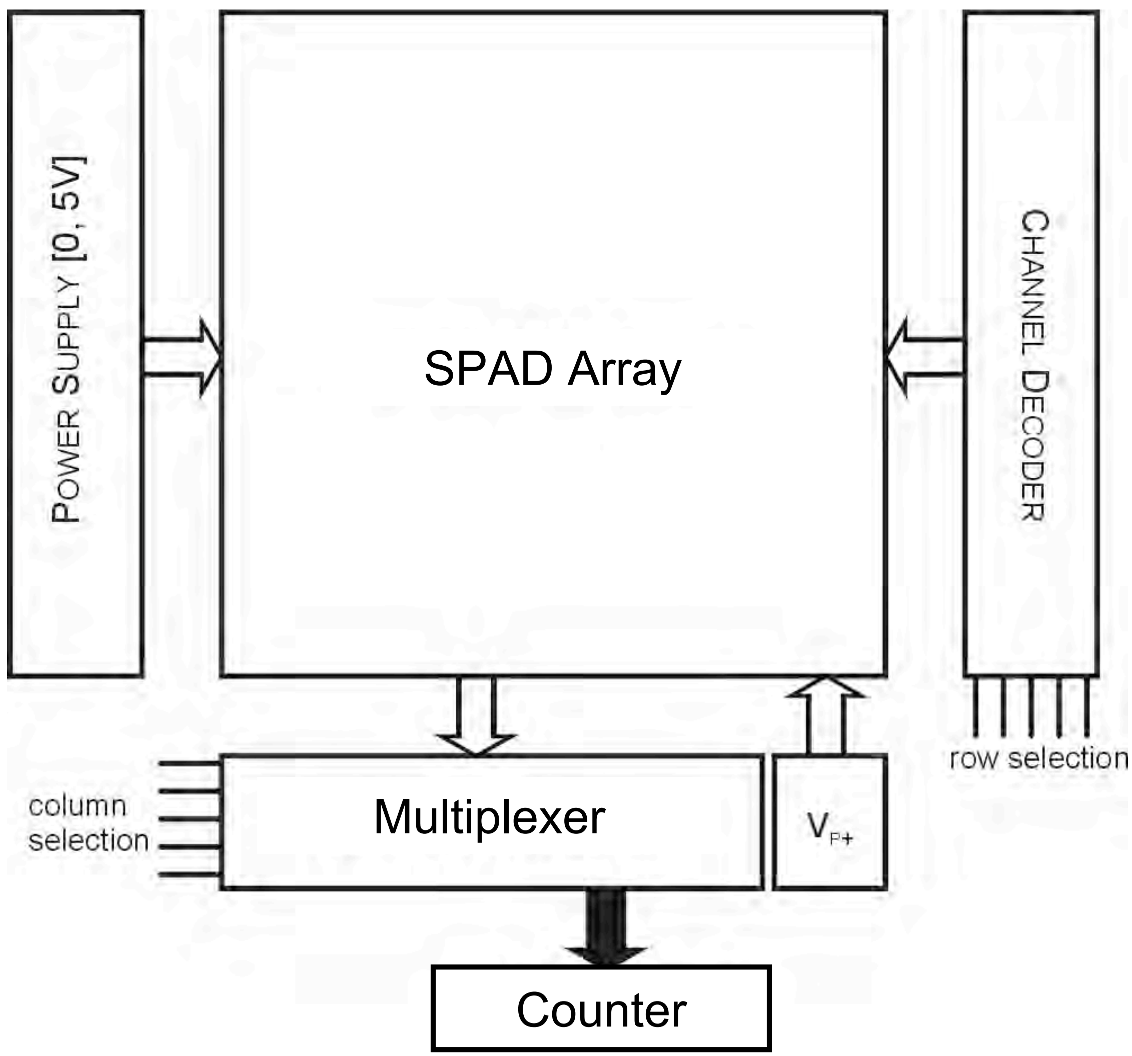
Performance:

- Pertiming jitter: < 50ps
- dead time : 32ns

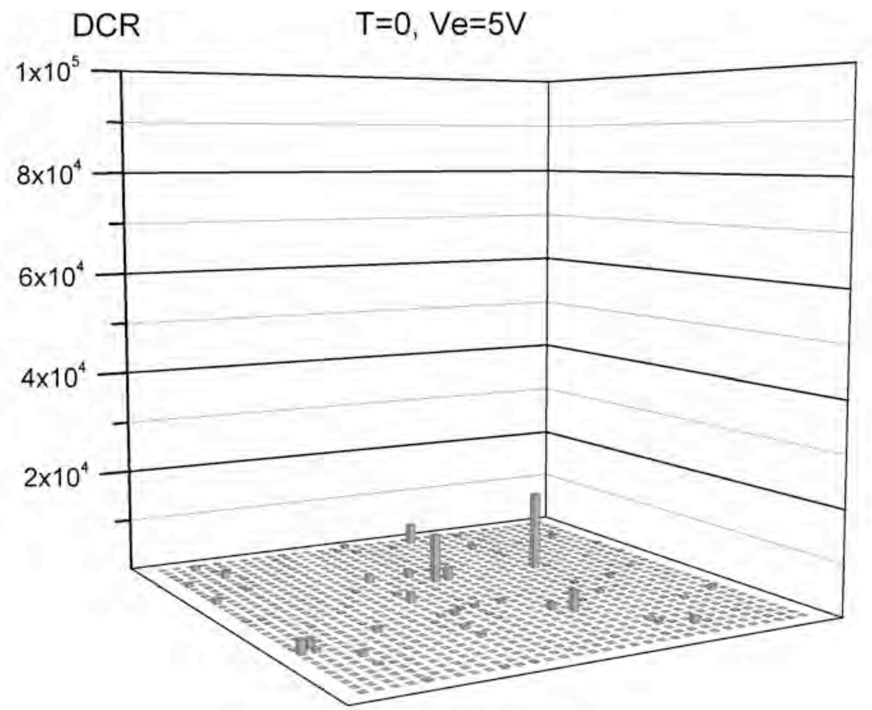
Potential impact:

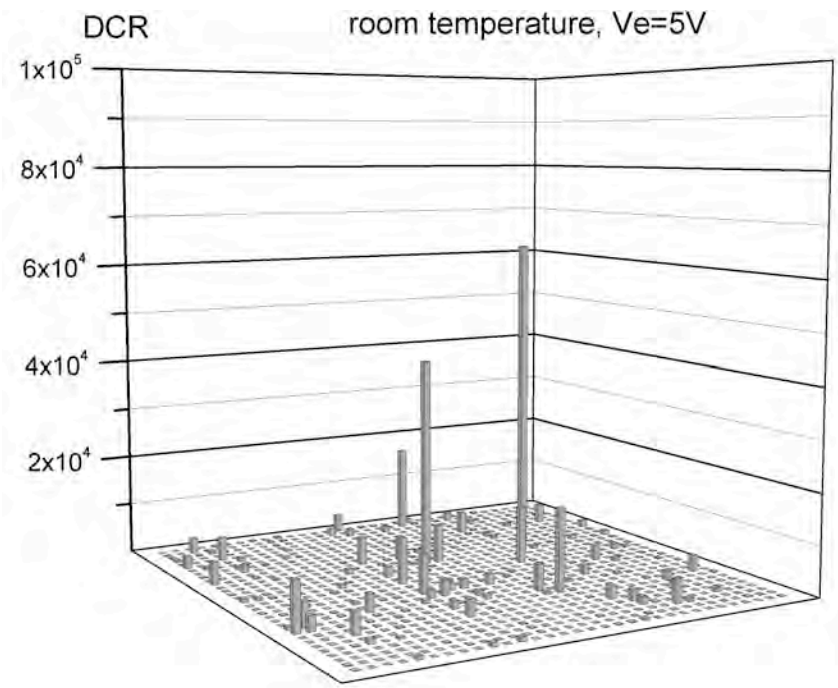
- Saturation
- Smearing

Experimental Setup for Imager

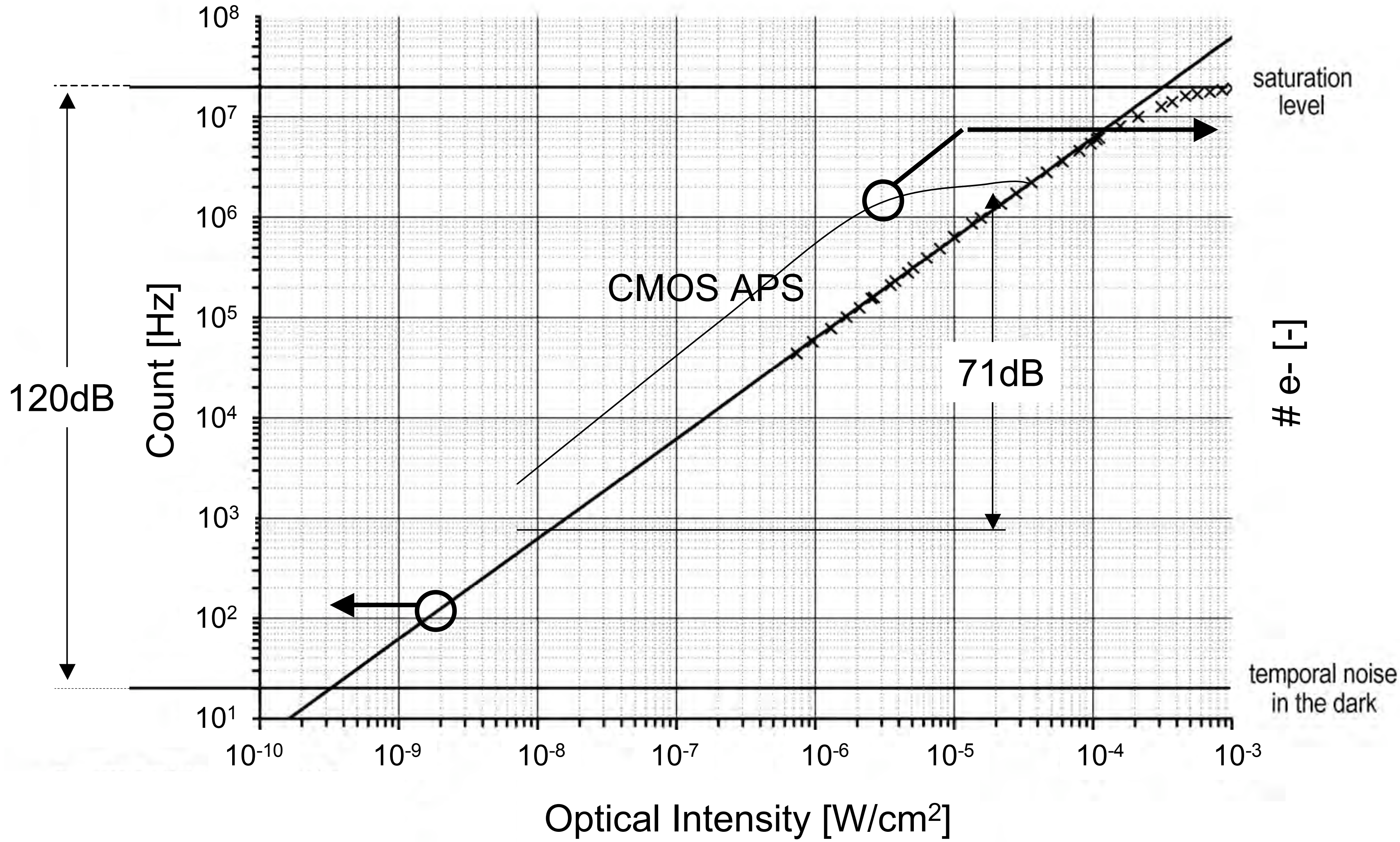


DCR

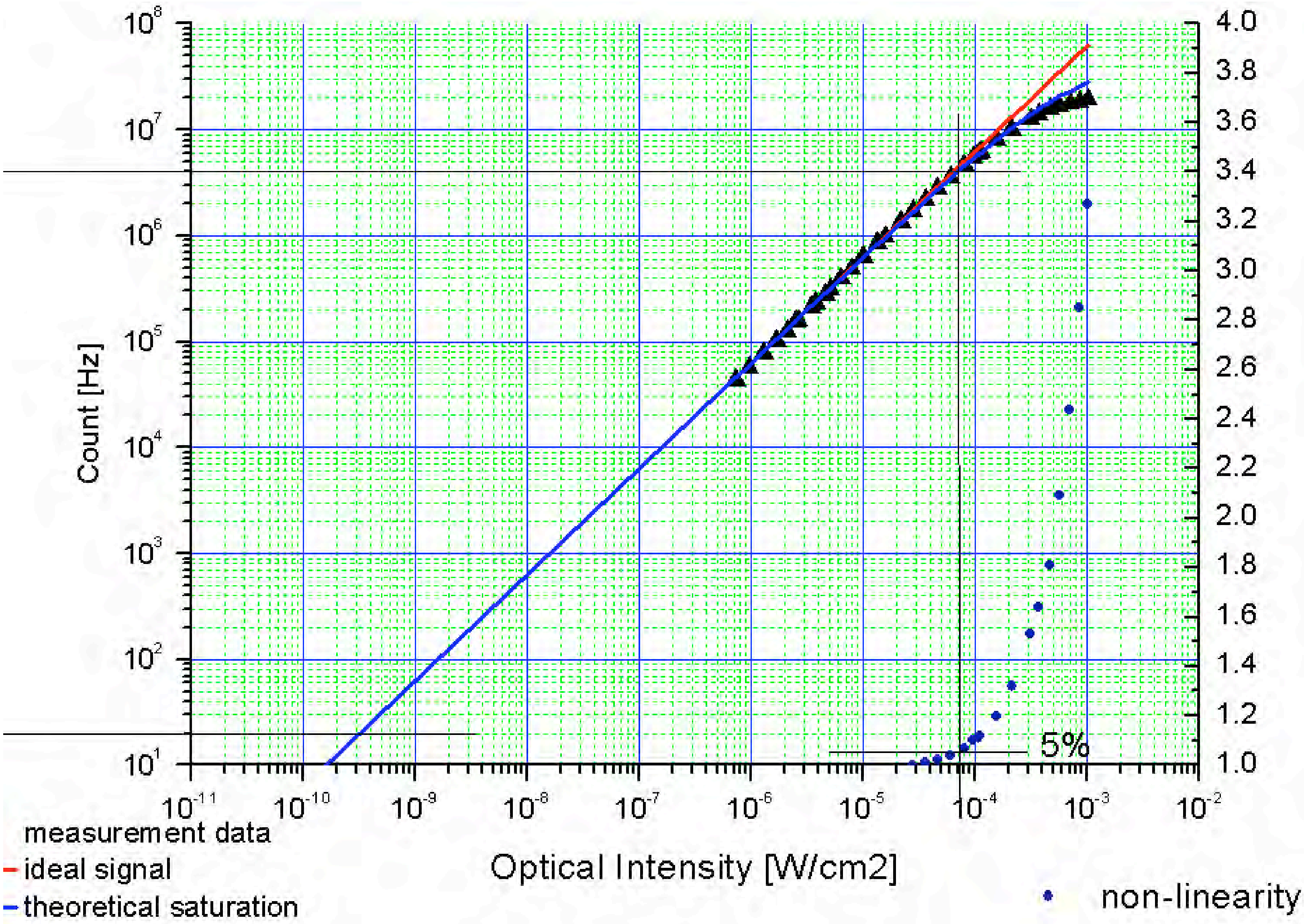

DCR
T=0, Ve=5V
1x10^5
8x10^4
6x10^4
4x10^4
2x10^4


DCR
room temperature, Ve=5V
1x10^5
8x10^4
6x10^4
4x10^4
2x10^4

Sensitivity and Dynamic Range

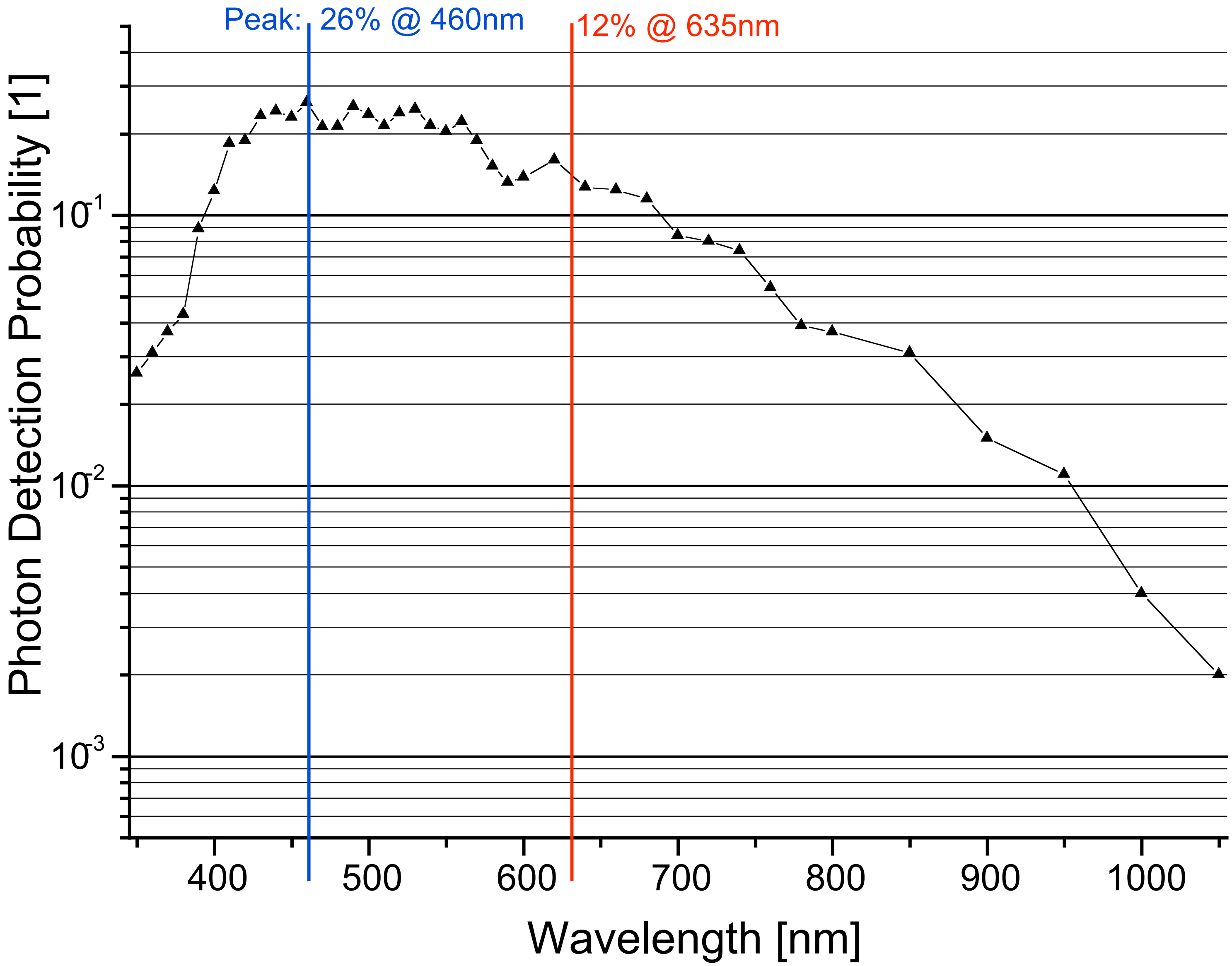


Linearity

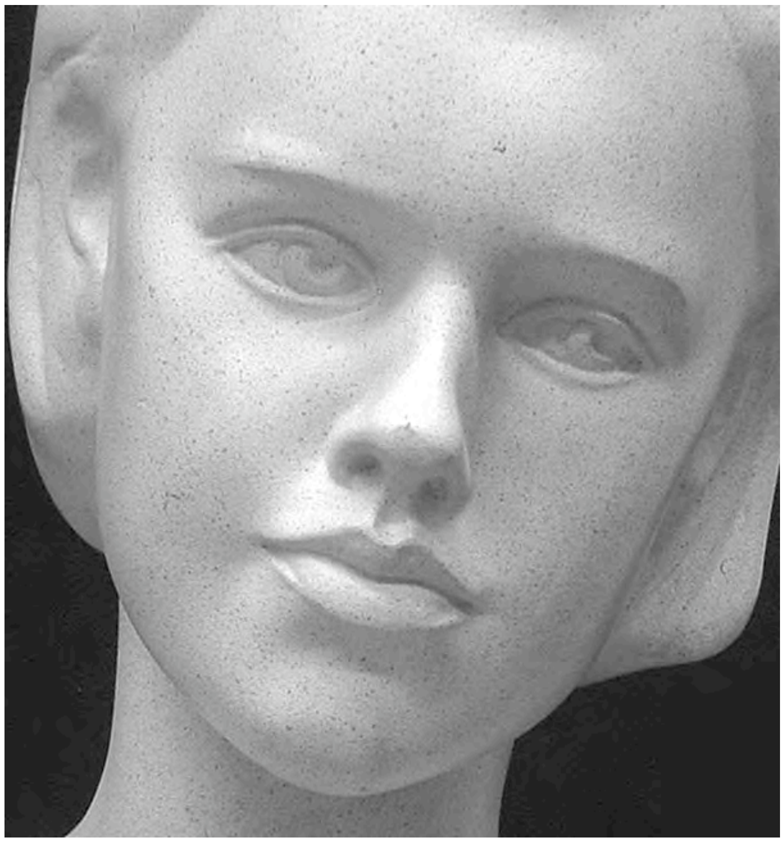


Count [Hz]
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
5%
10^-11
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
measurement data
ideal signal
theoretical saturation
Optical Intensity [W/cm2]
non-linearity

Photon Detection Probability



Example



High resolution Camera:
20cm x 20cm view

SPAD Camera:
32x32pixels

High Speed Example

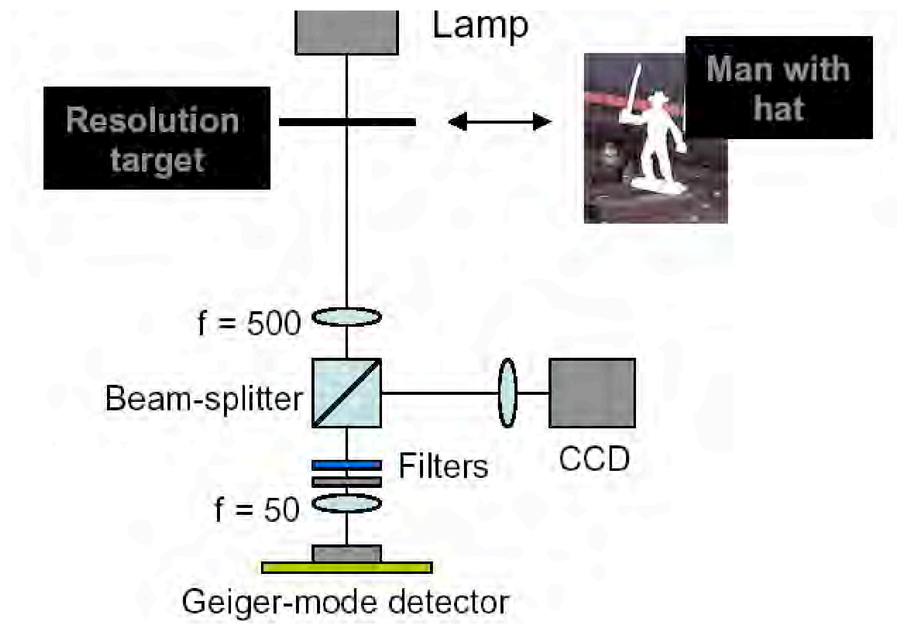
Features

- No measurable thermal noise (Poisson noise dominates)
- No measurable cross-talk, blooming, smearing

4μs 10μs 25μs 100μs 1ms

[Niclass, Rochas, Besse, Popovic, and Charbon, Transducers 2005]

High Sensitivity Example



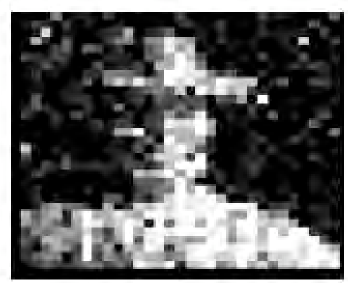
Deep Twilight

2 lx

Full Moon

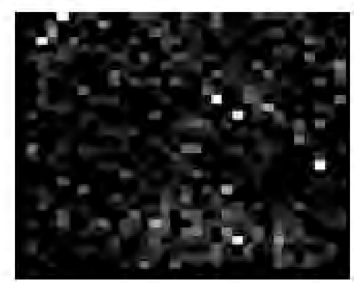
2×10^{-1} lx

Quarter Moon



2×10^{-2} lx

Starlight



2×10^{-3} lx

Intensity Performance Summary

Parameter	**Value**
Minimum Integration Time	4μs
Maximum Pixel Dynamic Range	120dB
Optical Intensity @ SNR=0dB	$1.3x10^{-3}$ Lx
Dark Count Rate (DCR) T=room/0^{o}C	350Hz/75Hz
Pixel Fillfactor	1.1%
Photon Detection Probability (PDP)	1-26%

Conclusions

- Significance and applications of 3D imaging
- Fabricated 1k pixel SPAD array in standard CMOS technology
- psec (μm) accuracy reached with mW laser source
- Chip power dissipation <1mW
- High sensitivity, dynamic range, and linearity for 2D applications

Future Work

- VGA pixel arrays
- Count / Read-out parallelization
- Pixel-level and column-level time-to-digital converters (TDCs)
- Pitch reduction
- On-chip basic computation
- Color

Future Directions

- qCAD
- Single photon telecommunications
- Accelerated DNA sequencing
- Laserless ultra-short range quantum communication and computing
- Data management

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