Single-Photon Imaging: Myth and Reality

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KISS Workshop:

UV Instrument Technologies

Delft Institute of Microsystems and Nanoelectronics

INSTITUTE FOR SPACE STUDIES

Outline

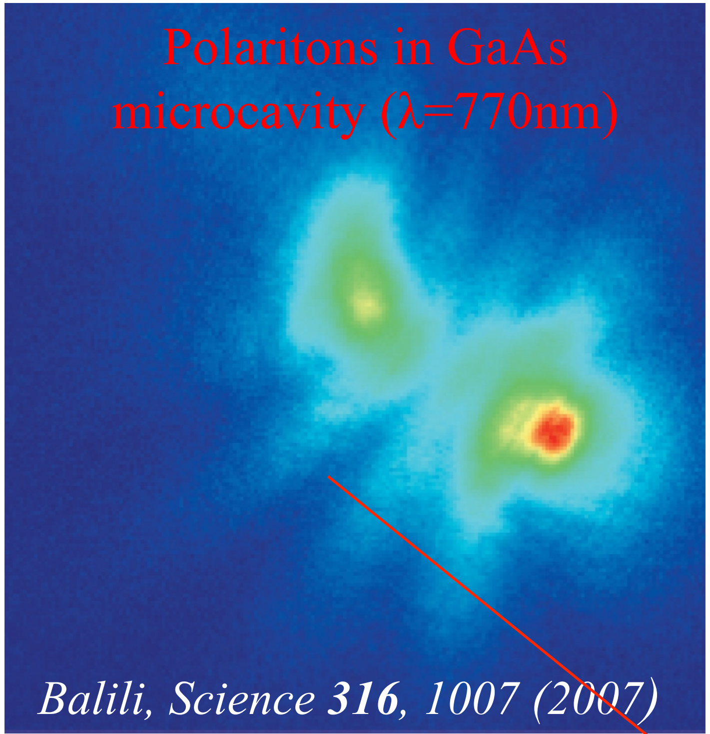
- Making the Case for Single-Photon Imaging
- Solid-State Single-Photon Detection
- From Pixel to Imager
- Rad-hardness
- The Myth and the Challenges

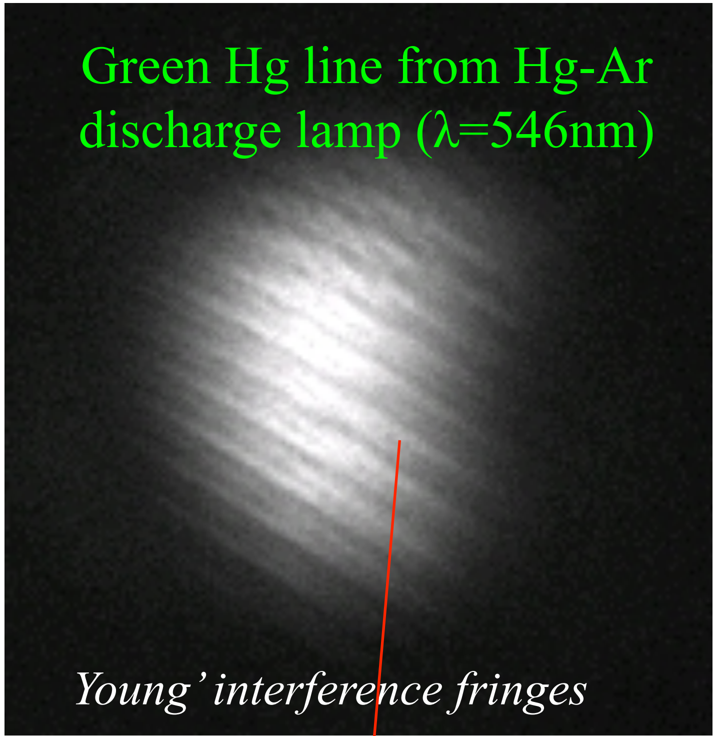
Making the Case for Single-Photon Imaging

Why Single-Photon Imaging?

- Single-photon imaging is good for
  - Time-correlated single-photon counting
  - Photon time-of-arrival
  - Photon correlation (ps~us)
- Single-photon imaging *not* good for
  - Ultra photon-starved situations (1 photon per minute – pixel)
  - Cooling and cost are not an issue!

Hanbury-Brown Twiss

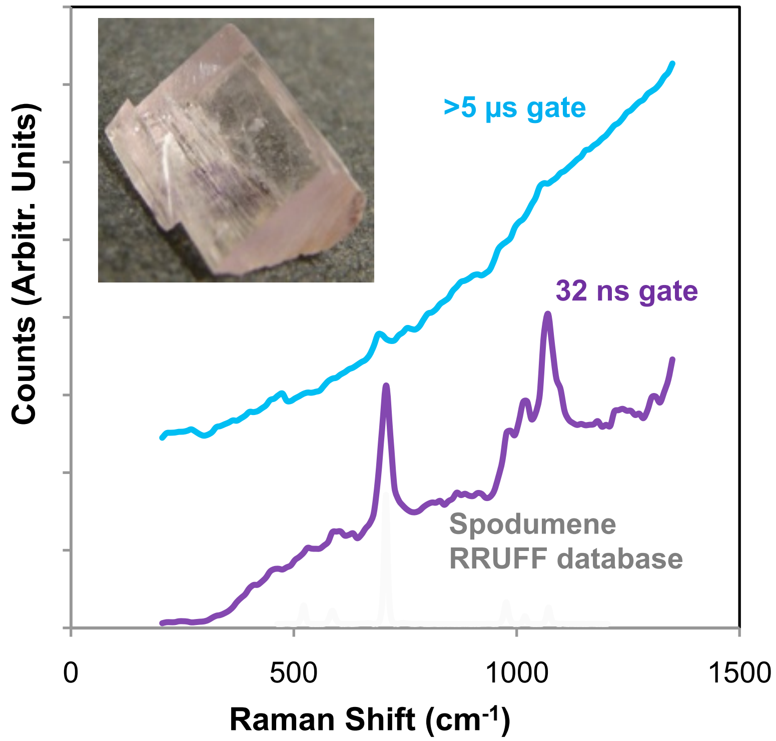


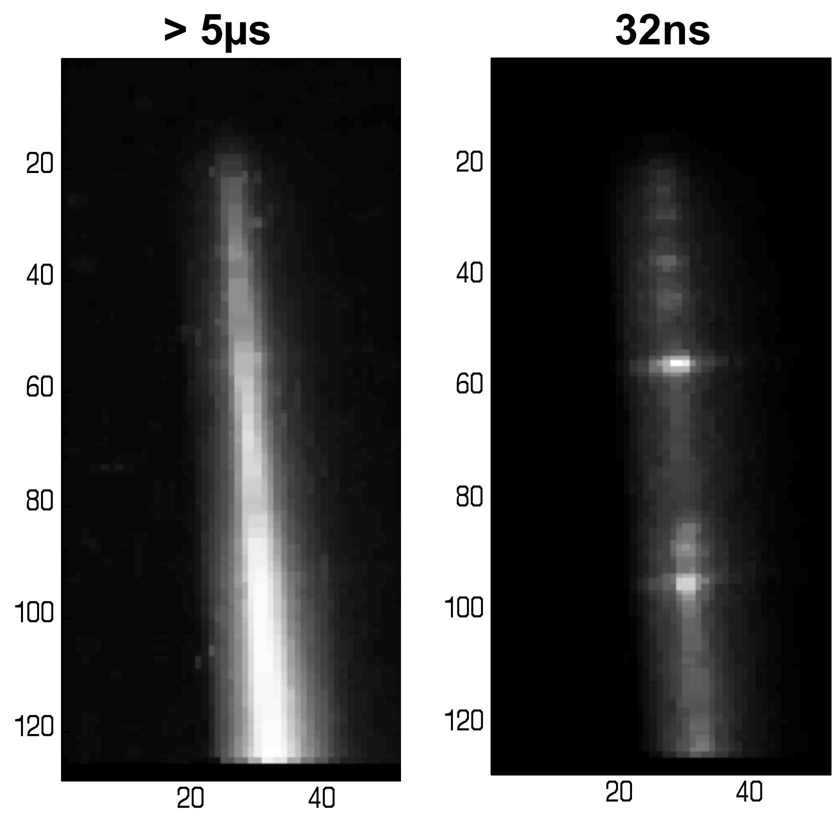


Photon states

	Incoherent	Coherent		Thermal
$g^{(1)}(0)$	0	1	=	1
$g^{(2)}(0)$	1	1	≠	2

Time-Resolved Raman





J. Blacksberg, Y. Maruyama, E. Charbon, G. Rossman, to appear, *Opt. Letters* (2011)

From Astronomical to Microscopic

- Super-resolution Microscopy
  - Stimulated Emission Depletion (STED)
  - Single Plane Illumination Microscopy (SPIM)
  - Scanning Photoionization Microscopy (SPIM)
- Molecular Imaging
  - Fluorescence Lifetime Imaging Microscopy (FLIM)
  - Förster Resonant Energy Transfer (FRET)
  - Fluorescence Correlation Spectroscopy (FCS)
- Nuclear Medicine
  - Positron Emission Tomography (PET)
  - PET & Magnetic Resonance Imaging (MRI)
  - Single-photon Emission Computer Tomography (SPECT)

Other Space Applications

- Raman Spectroscopy *in situ* (on the ground, from orbit)
- LIDAR in space
- 3D vision for planetary approach and landing
- Time-resolved X-ray imaging
- Time-resolved gamma-burst imaging

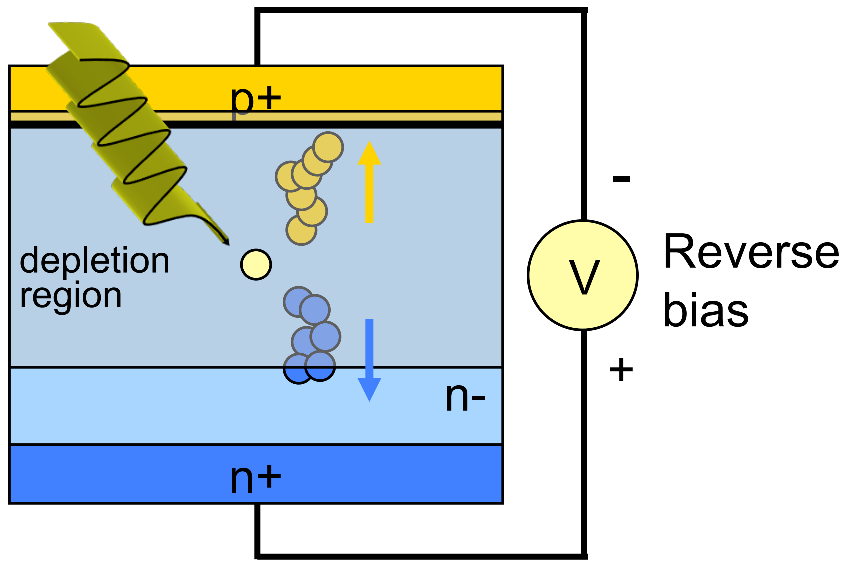
Solid-state Single-Photon Detection

Multiplication in Silicon

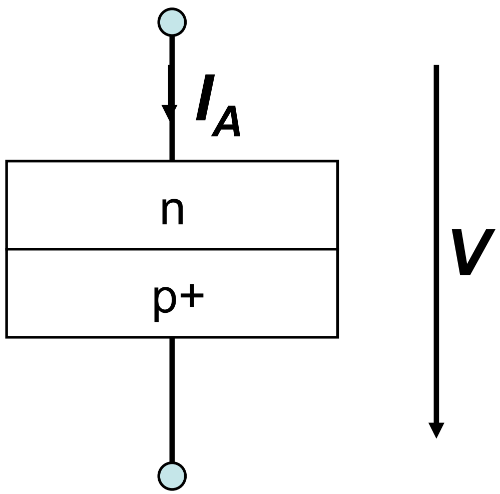
- *Review*:

  Photon to electron - Secondary electron - Multiplication

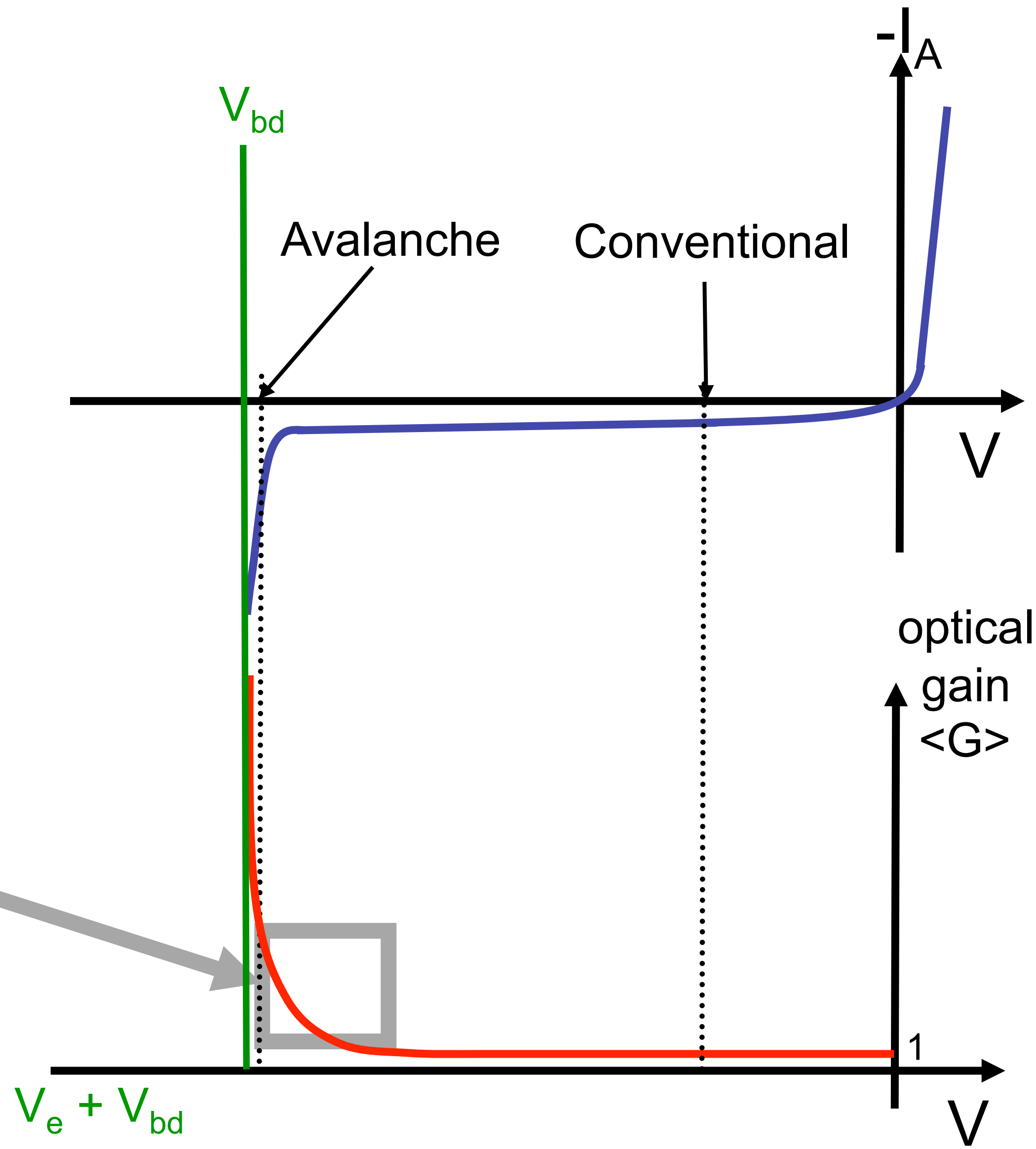
  Multiplication in depletion region by *impact ionization*



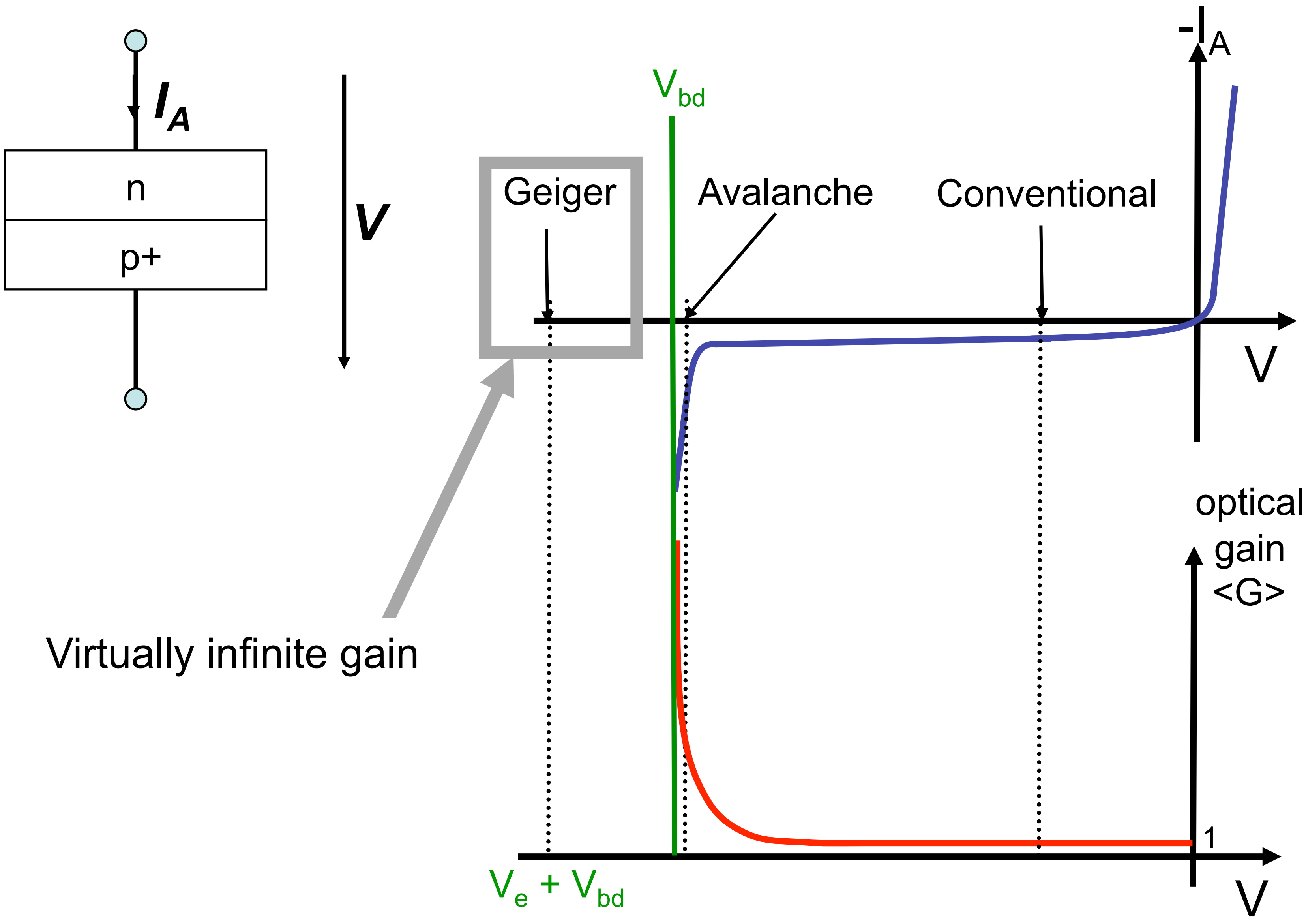
Linear (or Proportional) Mode



High variability of gain
From bias

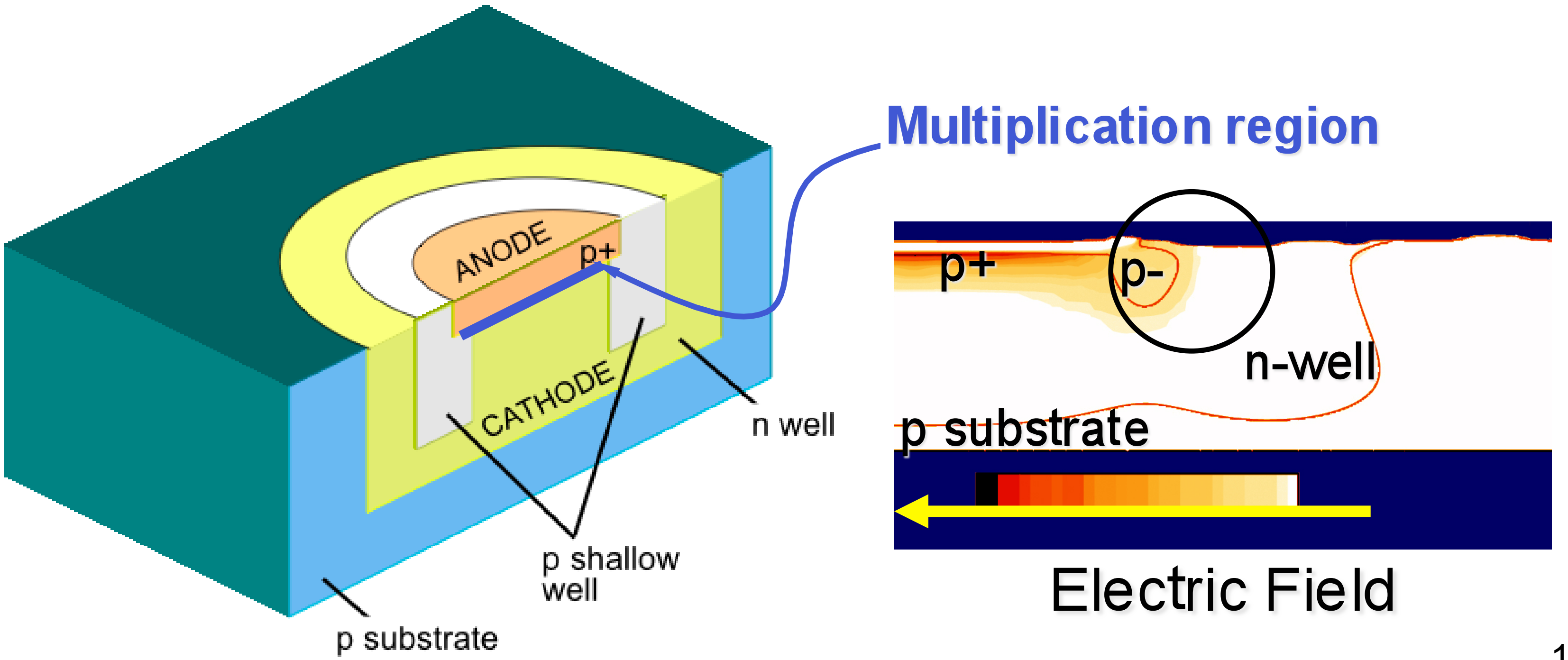


Geiger Mode (SPAD)



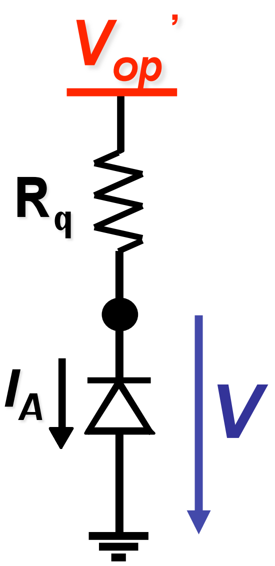
Modern Planar Processes

- p- guard ring for electric field reduction in edges
- Prevention of premature edge breakdown
- Creation of zone with constant electric field

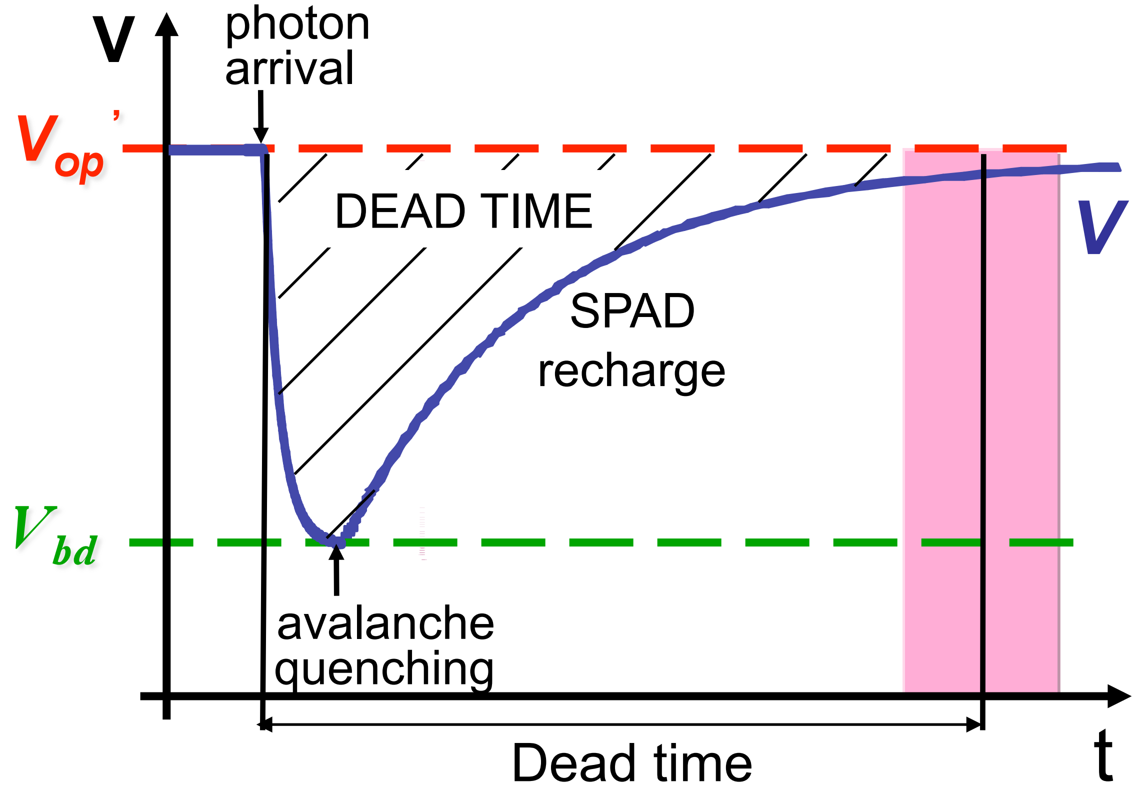


Quenching

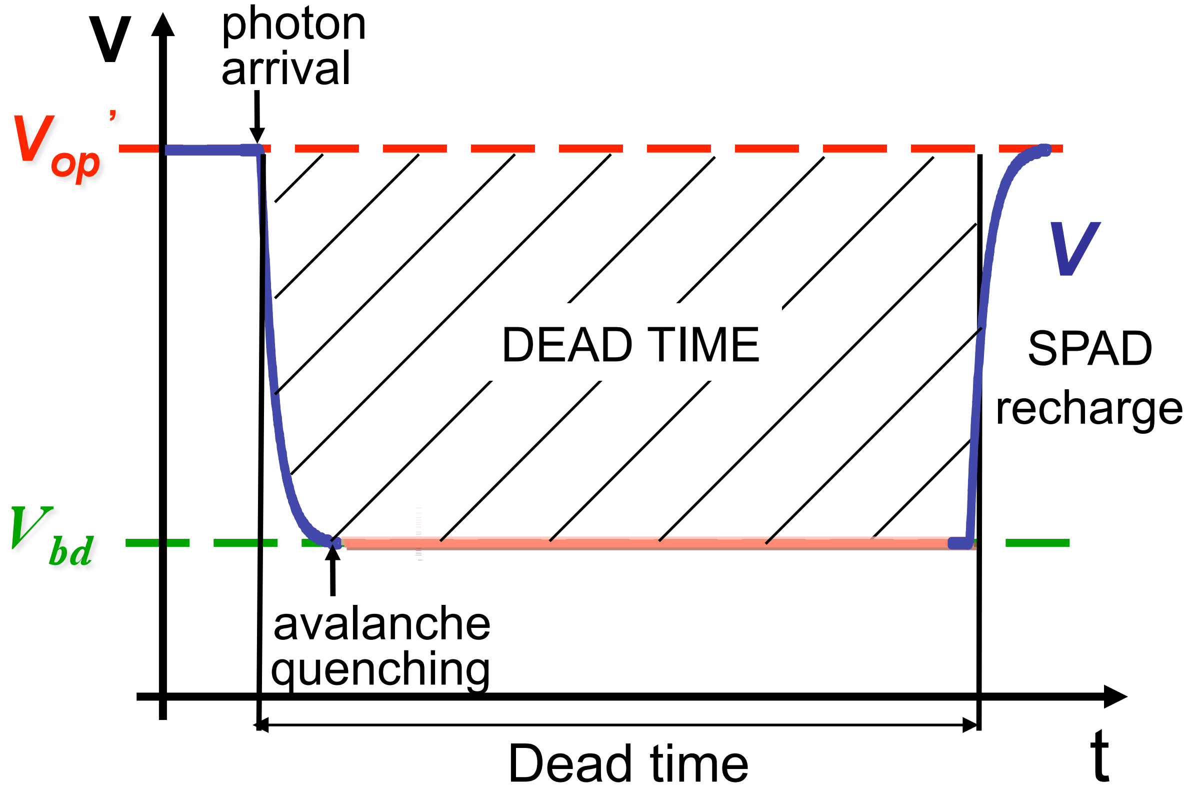
Passive quenching:



Operation cycle:



Controlling Dead Time



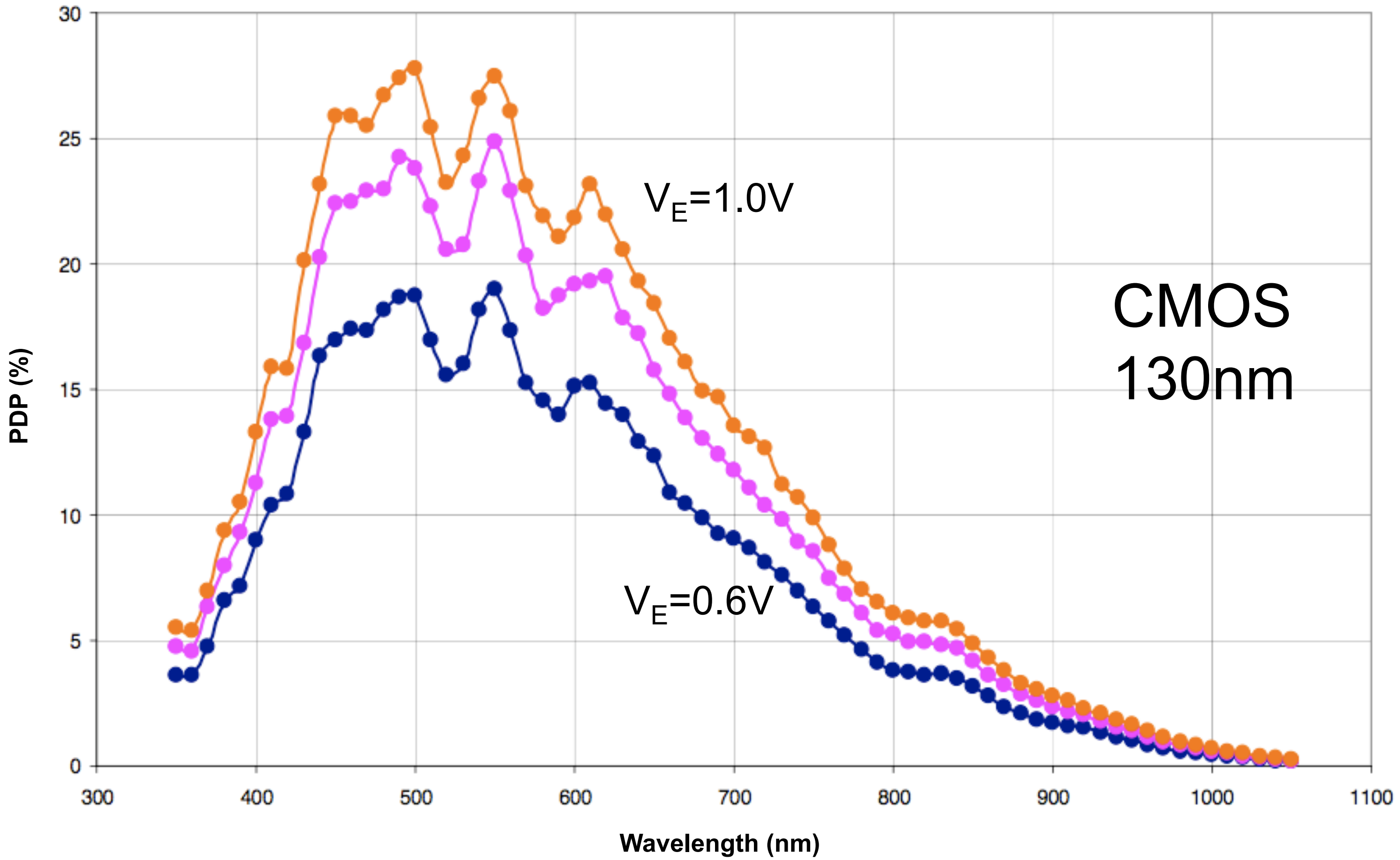
Integrated SPADs

- ***Dead time…*** **6ns~200ns**
- ***Afterpulsing*****…<1~10% @ dead time**
- **Dark counts… 0.004~10Hz/um^2 @ t=300K**
- **Photon detection probability** (PDP) ***10~70%***
- **Timing resolution… 100~250ps**

… and in SPAD imagers

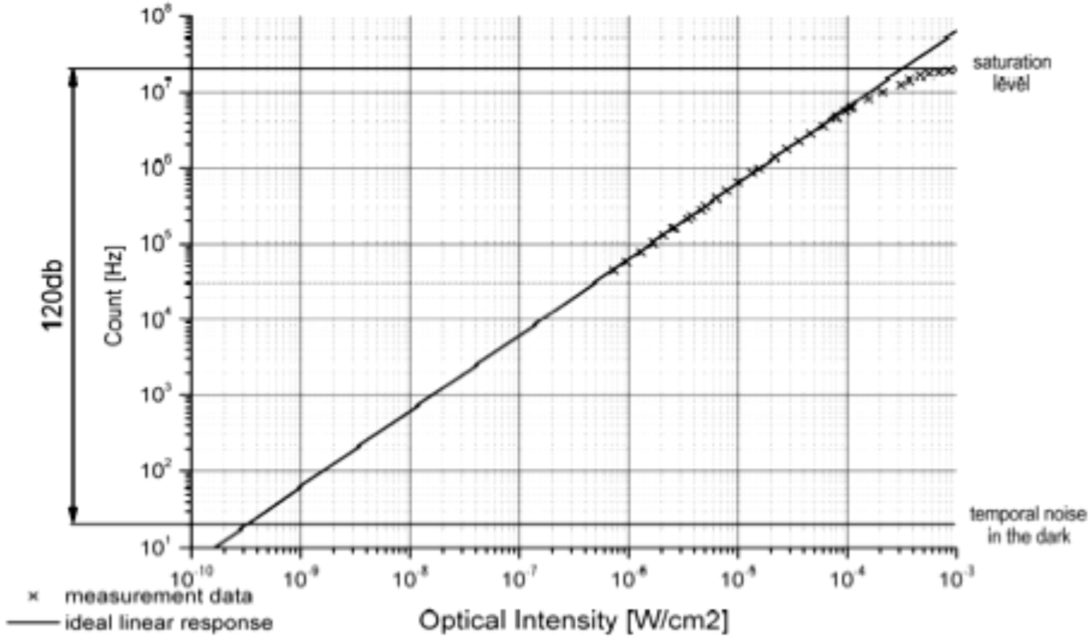
- **Cross-talk… <1%**
- **PDP Uniformity <1%**

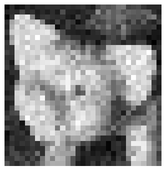
SPAD Spectral Performance



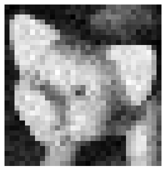
Richardson *et al. PTL* ***21****(14), 1020-1022 (*2009) / Ph.D. Thesis, 2010

Dynamic Range

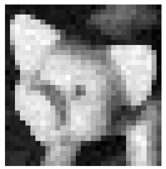




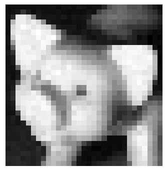
4µs



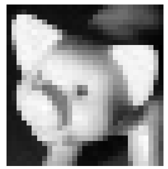
10µs



25µs

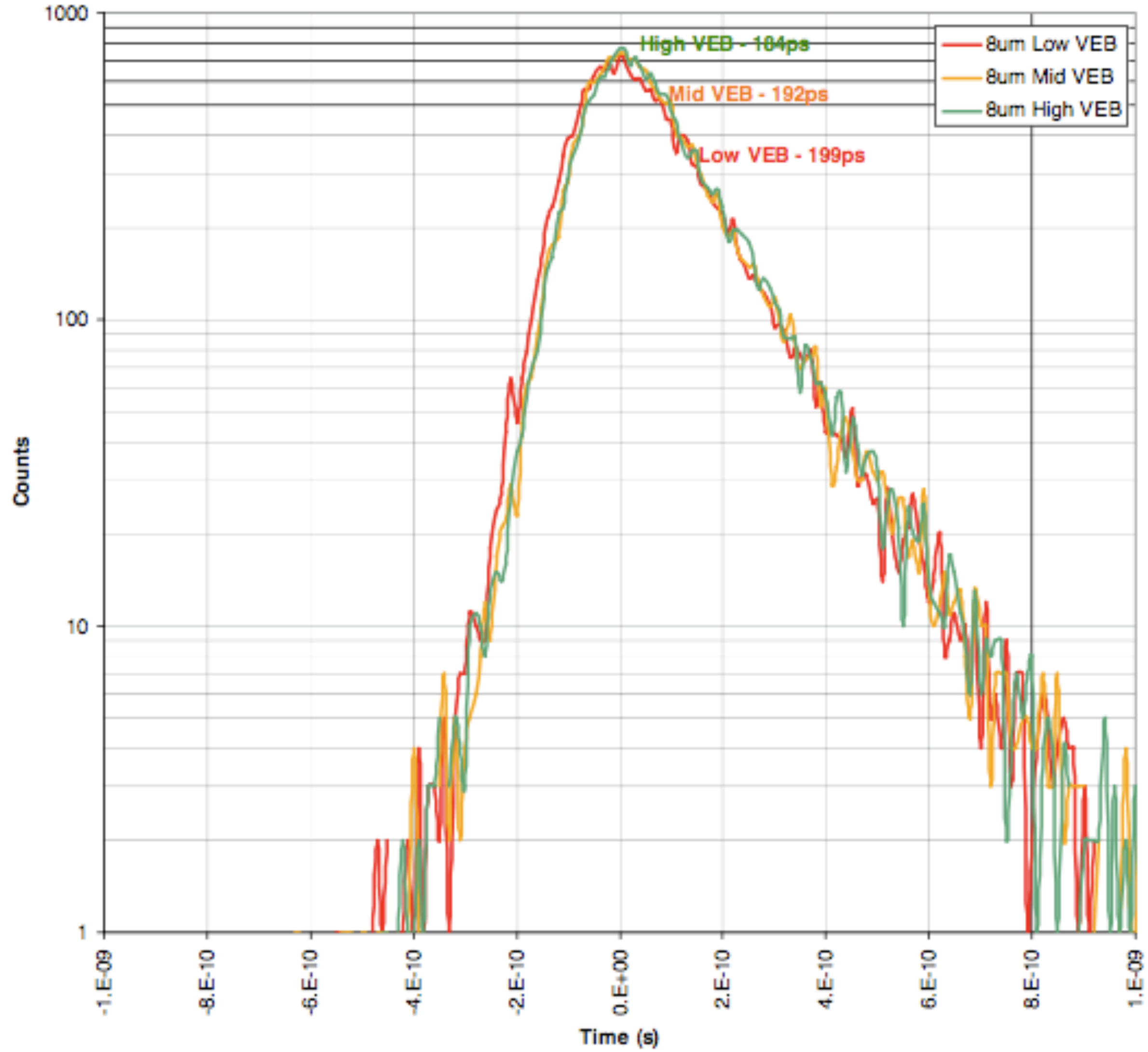


100µs



1ms

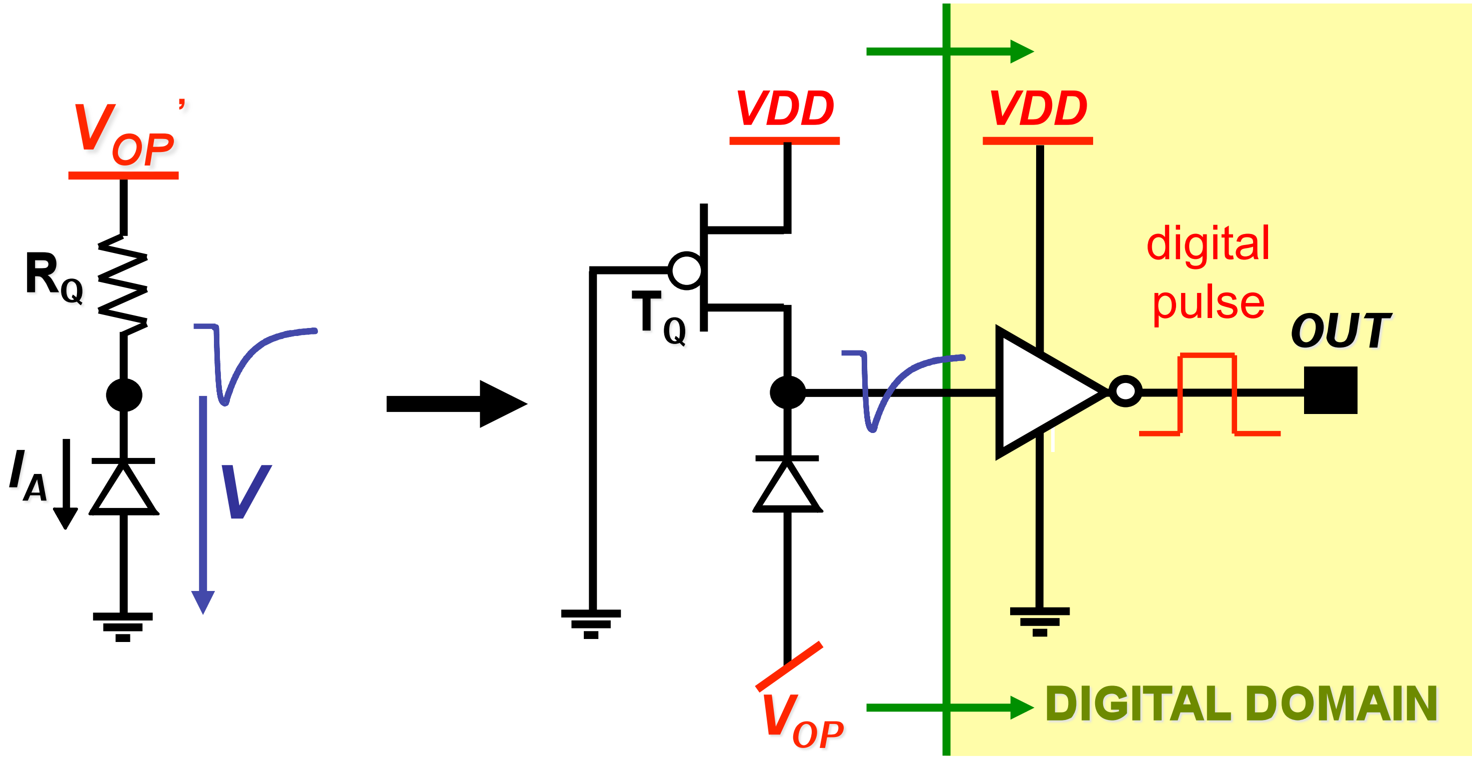
Timing Jitter



Richardson, Ph.D. Thesis 2010

From Pixel To Imager

SPAD in CMOS

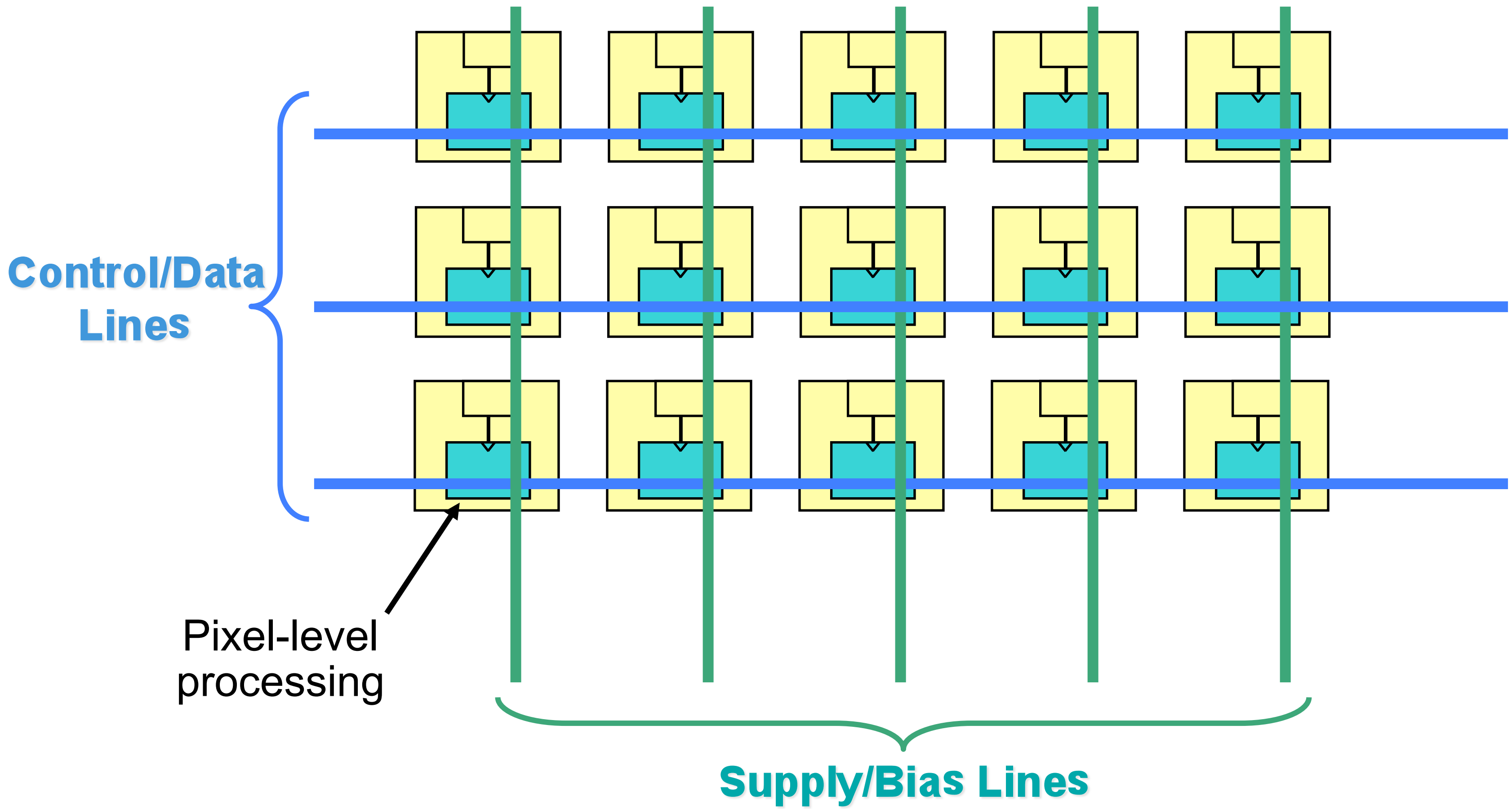


Passive quenching technique

Imaging: Three Architectures

1. Random Access Readout
2. Event-driven Readout
3. Fully-parallel Processing

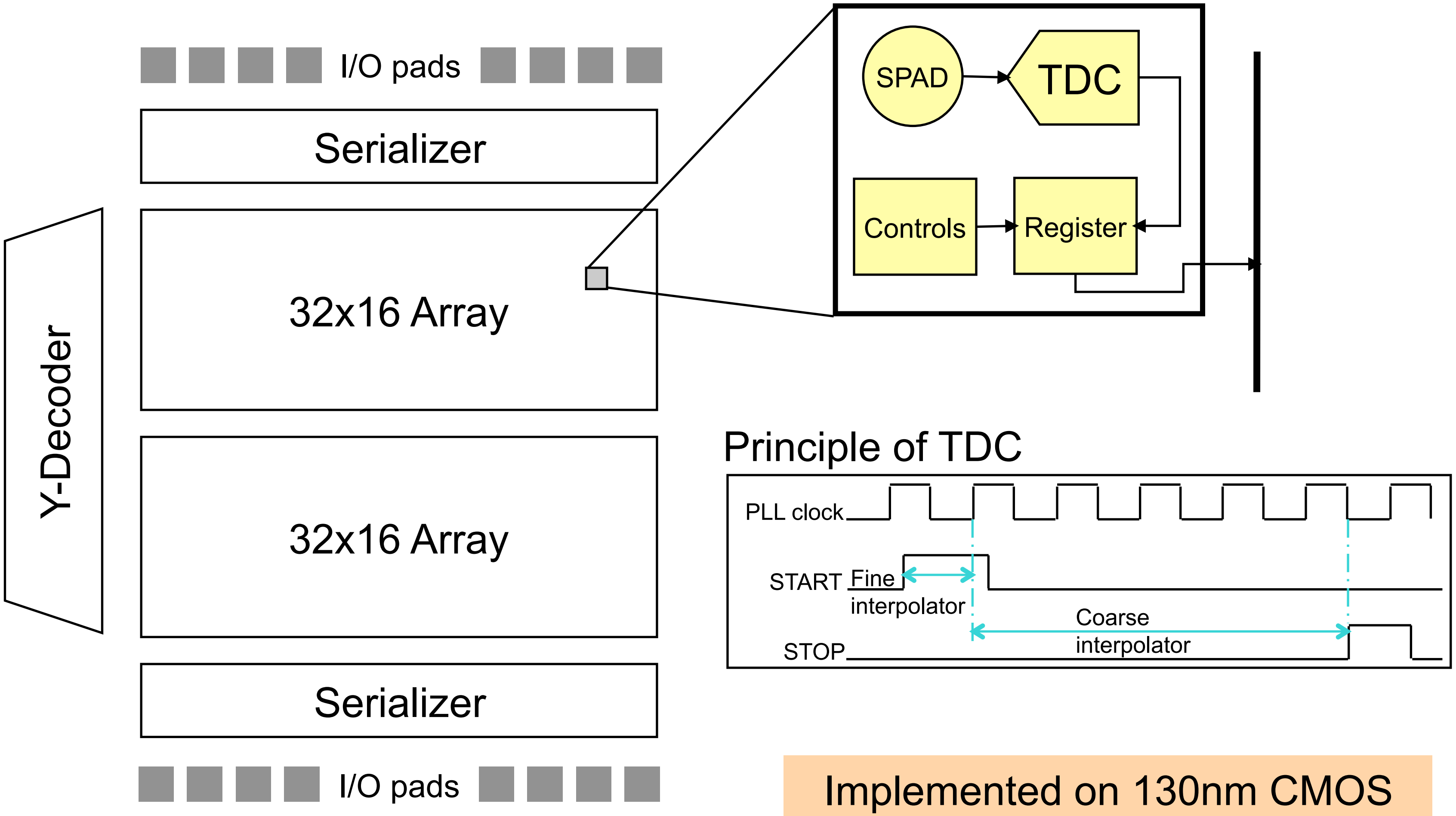
3. Fully Parallel Processing



Pros and Cons

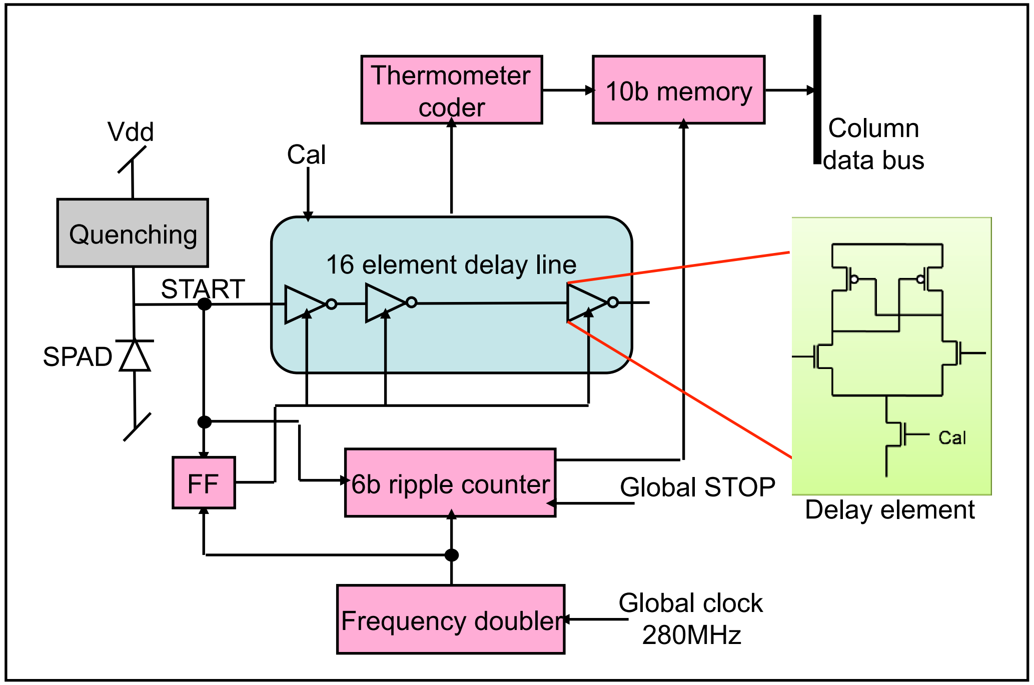
- Pros
  - Full parallelism
  - No photons are lost within detection cycle
- Cons
  - Readout bandwidth
  - Substrate/supply noise

MEGAFRAME: Massive Integration in DSM



Implemented on 130nm CMOS

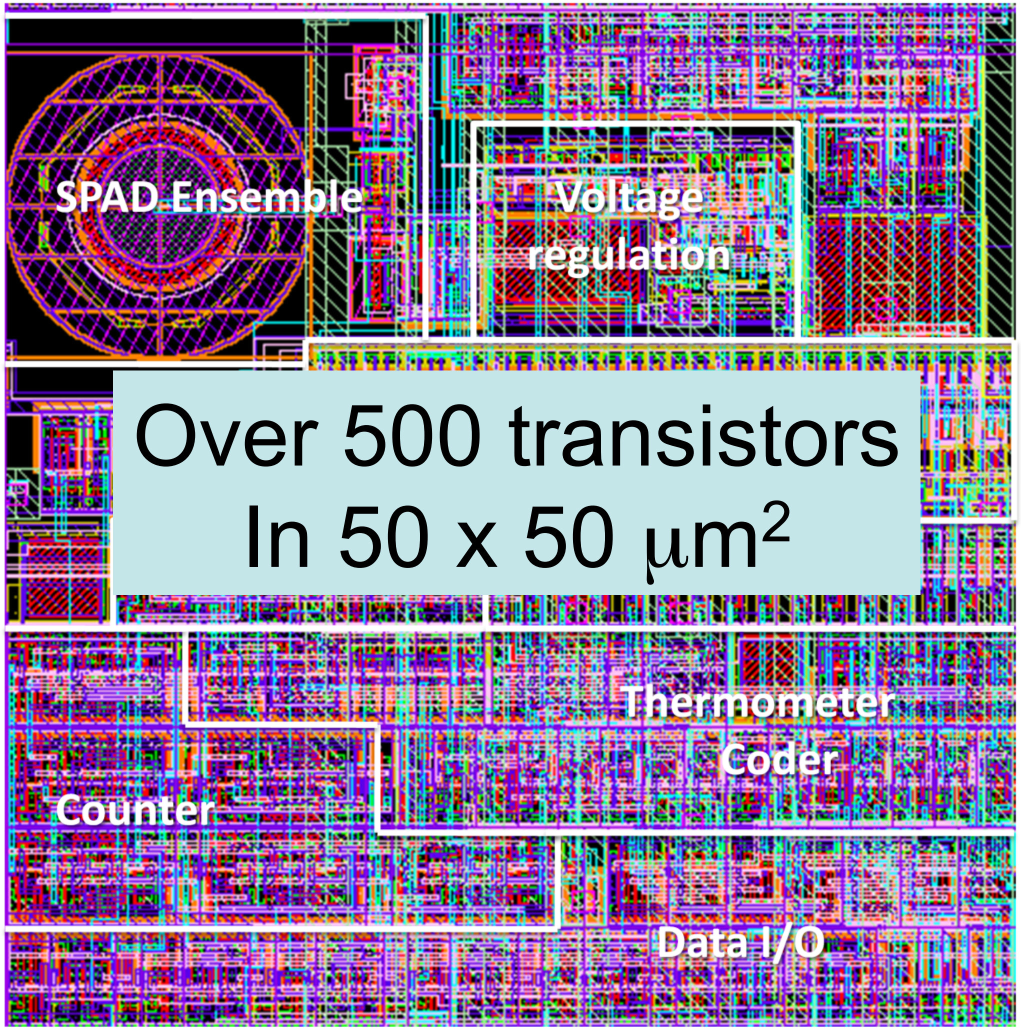
Pixel Schematic



Gersbach, Charbon, et al., *ESSCIRC 2009*

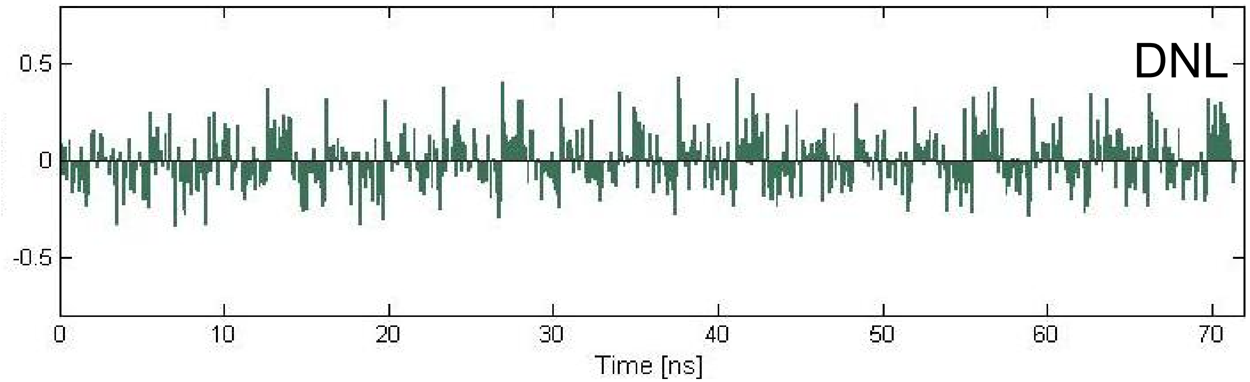
Pitch: 50um
Max. Resolution: 119ps
Bandwidth: 1MS/s
Accuracy: 1.2LSB (INL)
Timing jitter: 128ps (FWHM)
Timing uniformity: < 2LSB

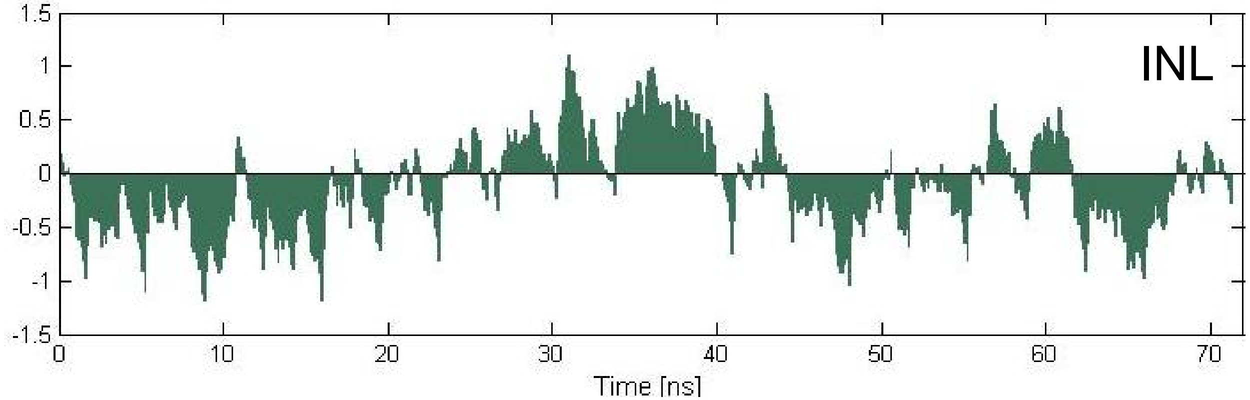
Pixel Layout



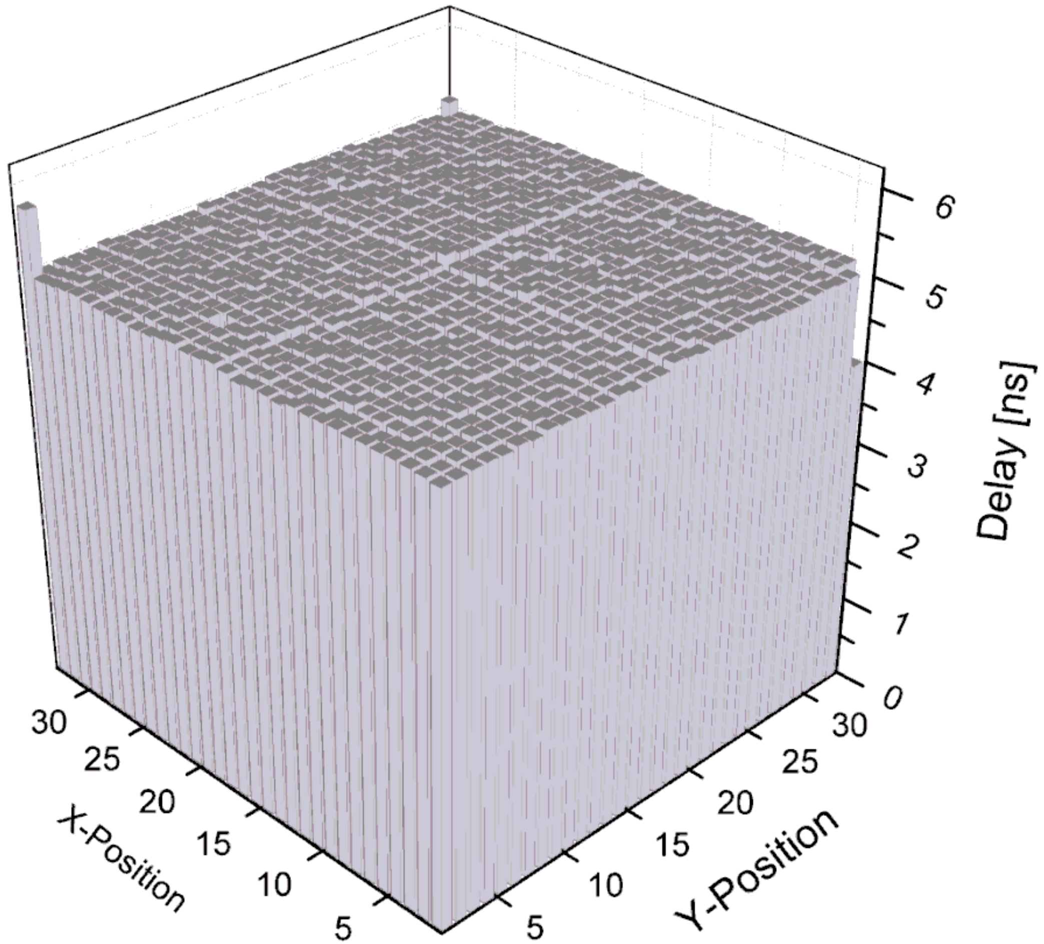
Over 500 transistors
In 50 x 50 μm^2

TDC Performance

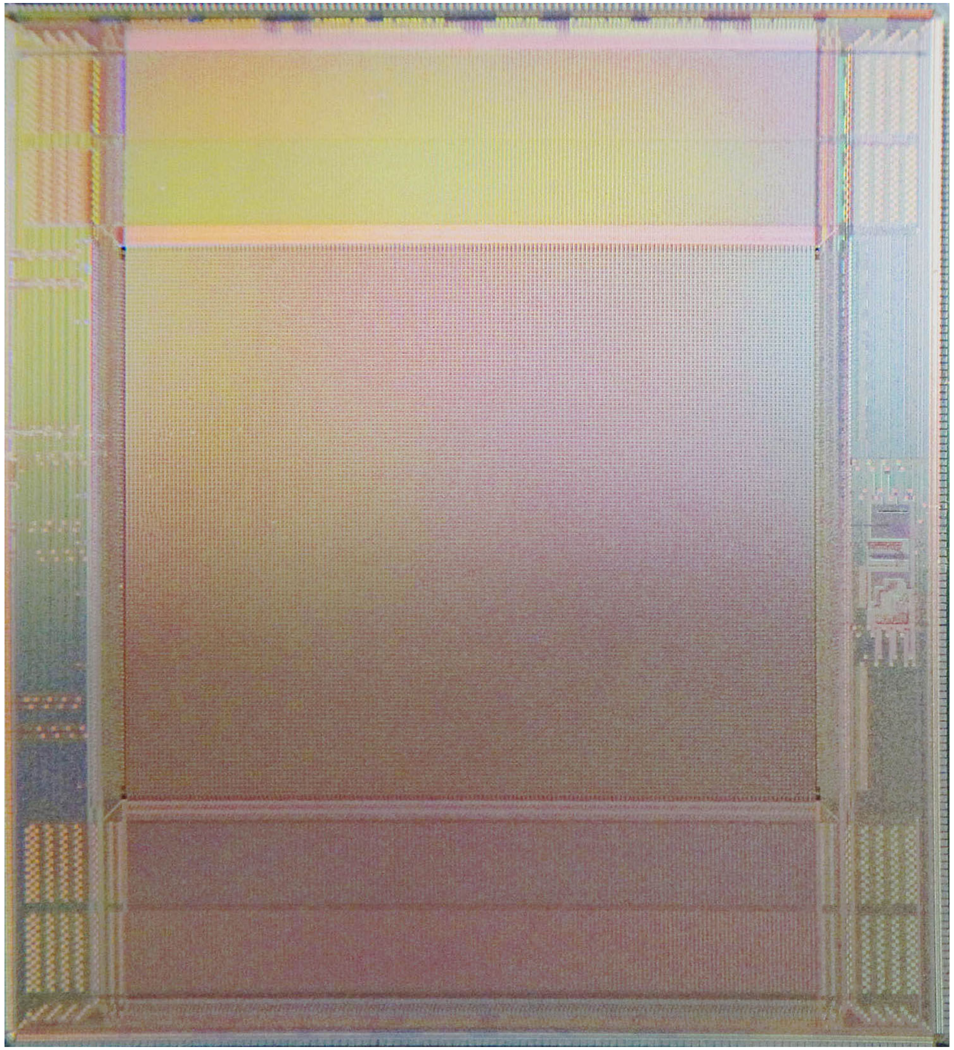




TDC Uniformity

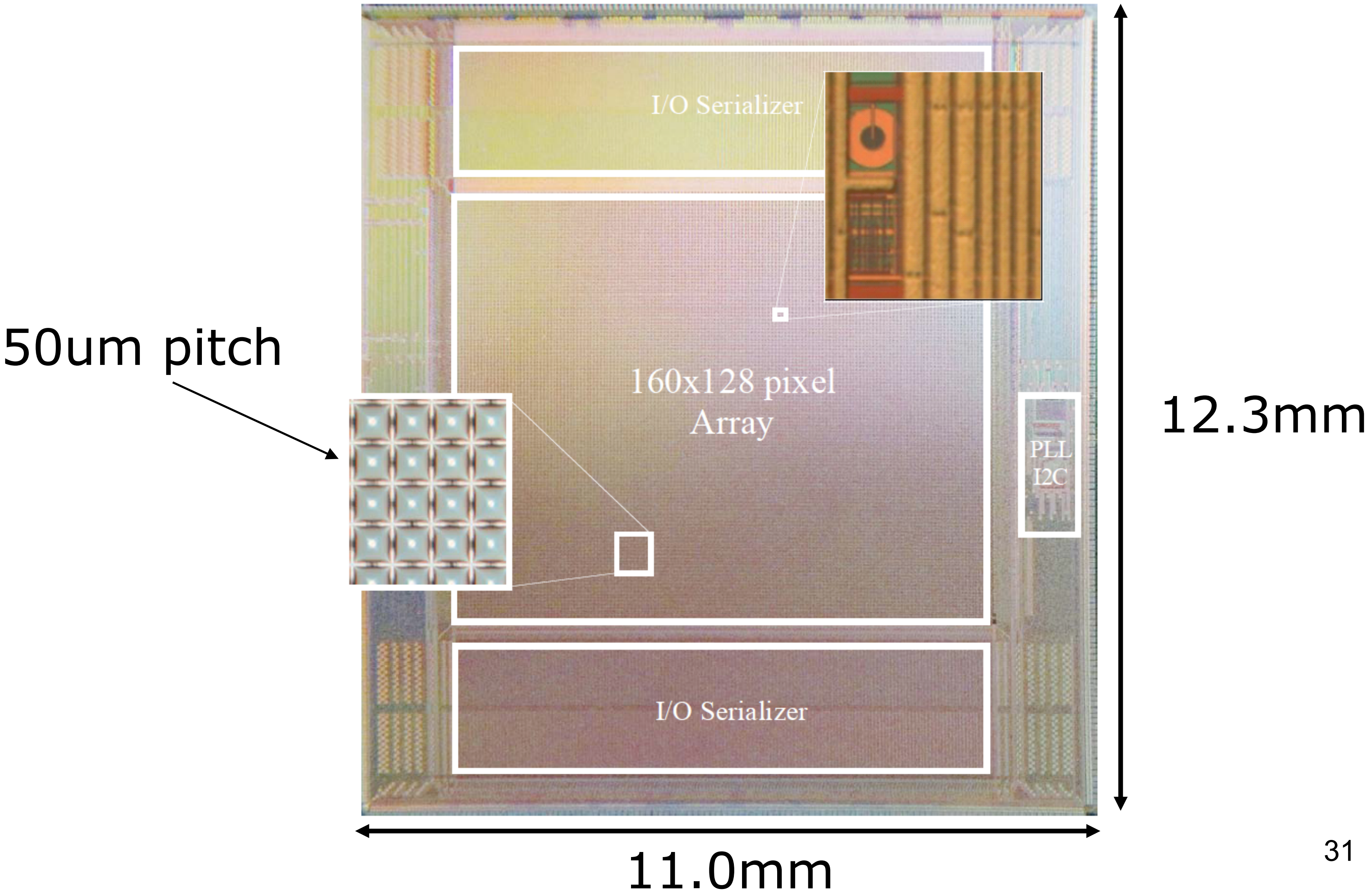


The Megaframe-128 Chip

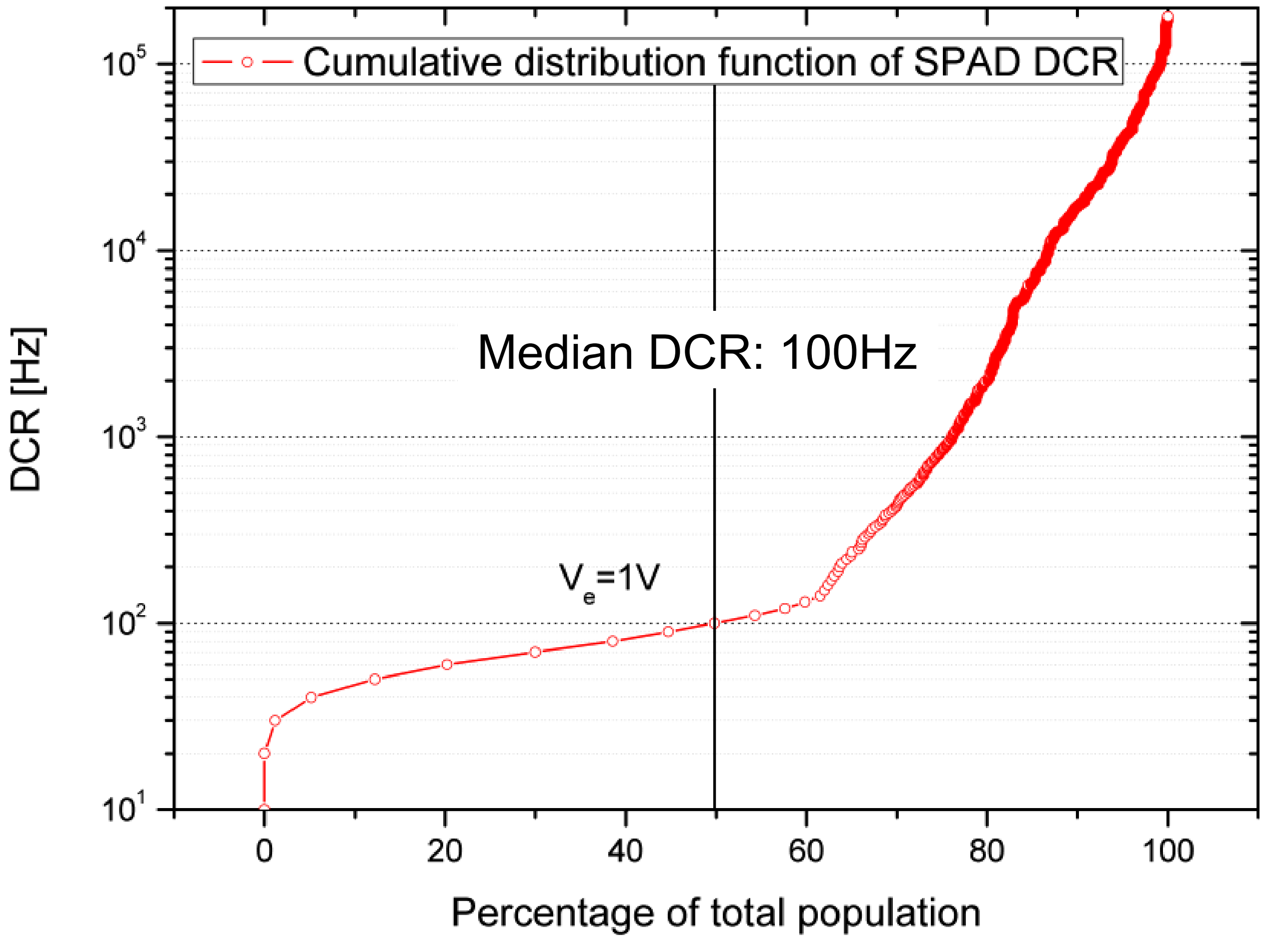


C. Veerappan, J. Richardson, R. Walker, D.-U. Li, M. W. Fishburn, Y. Maruyama, D. Stoppa, F. Borghetti, M. Gersbach, R.K. Henderson, E. Charbon, *ISSCC2011*

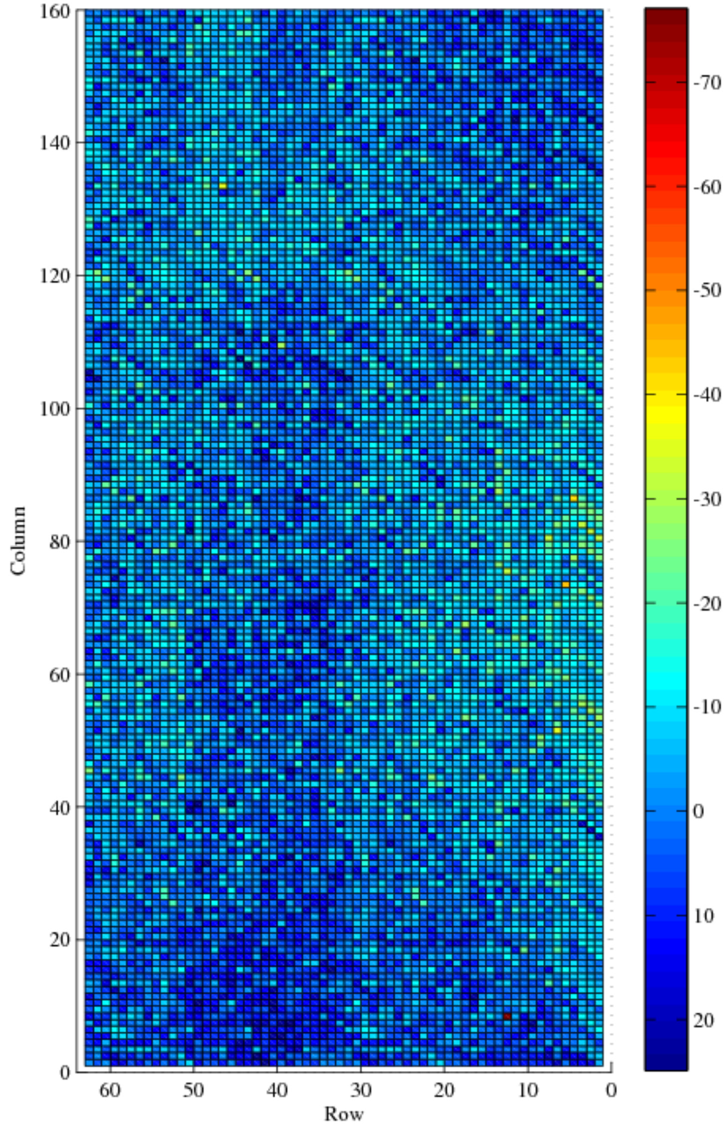
The Megaframe-128 Chip



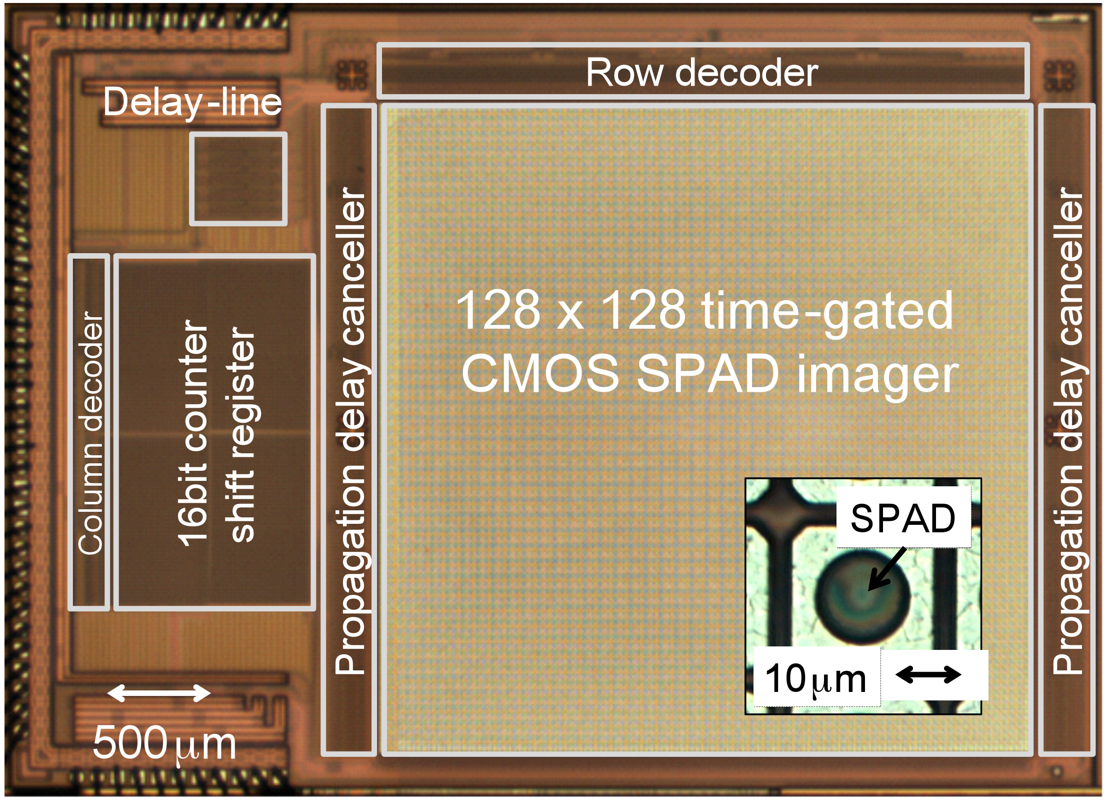
Dark Count Rate



Time–of–arrival Uniformity



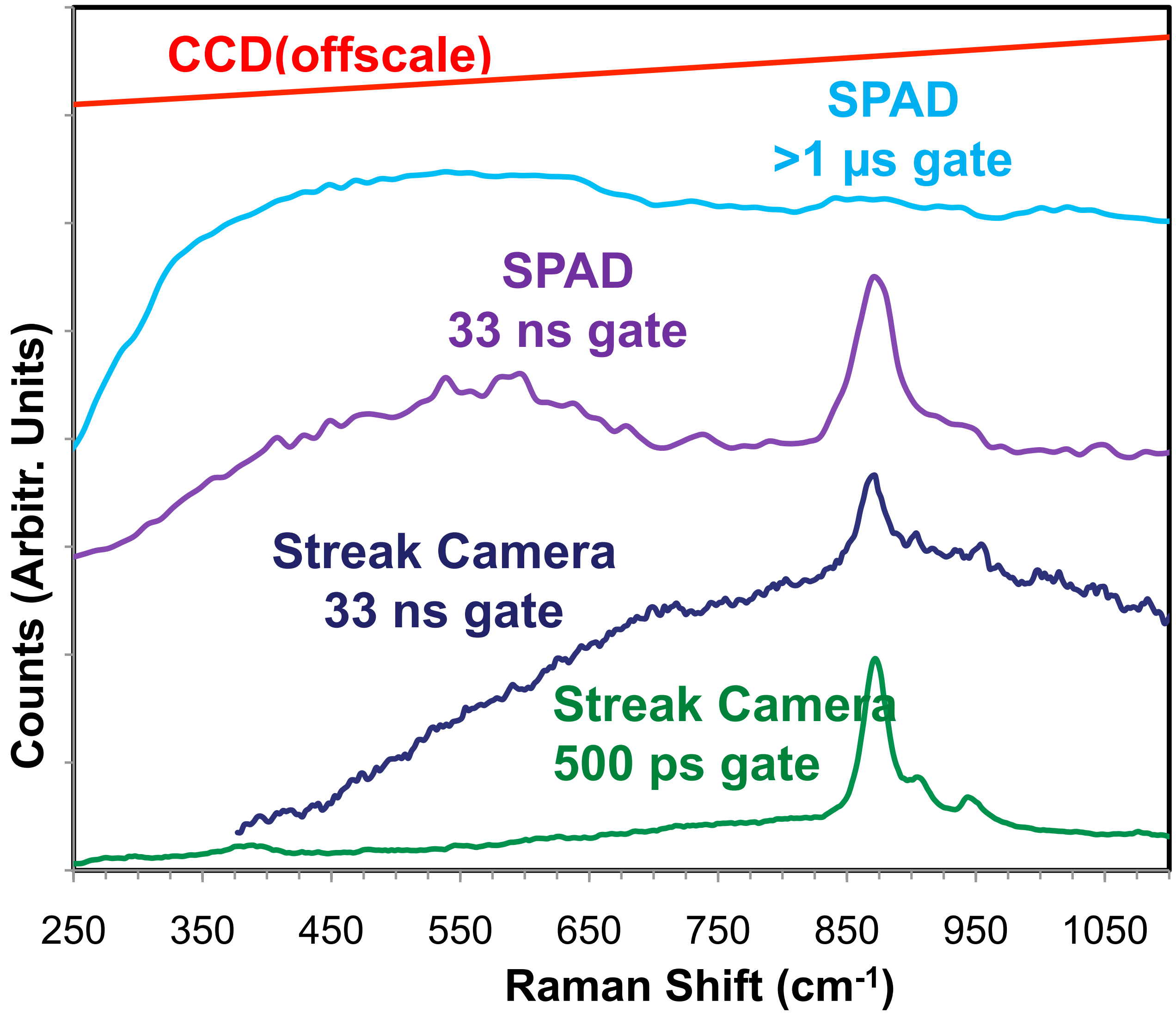
The Multi-Sensor Chip



- Time-gated SPADs
- IRF: 230ps
- Fully-parallel small pitch pixels
- DCR (median): 79Hz

Y. Maruyama and E. Charbon, **AN ALL-DIGITAL, TIME-GATED 128X128 SPAD ARRAY FOR ON-CHIP, FILTER-LESS FLUORESCENCE DETECTION,** *Transducers 2011*

Comparison with a Streak Cam



J. Blacksberg, Y. Maruyama, E. Charbon, G. Rossman, to appear, *Opt. Letters* (2011)

Rad-Hardness

Other Rays

Not only resilience to Gamma and Proton…

… also X-rays, Beta, and B-fields (9.4T)

Irradiation type	Source	Fluence/ Flux	Dose (Si)	Initial DCR	Final DCR	DCR after Annealin g (anneal time)
Gamma	Co60	10.46 rad/min	1.0 Mrad	153	569	276 (172 h)
X	Comet-Yxlon TU320-D03	4.3 AsV^2	0.25 mGy	540	545	540 (1 min)
		324 AsV^2	0.25 mGy	540	640	540 (1 min)
		900 AsV^2	0.5 mGy	540	701	540 (1 min)
Proton	Accelerator	$1.8x10^7 p/cm^2/s$ (11MeV)	40.0 krad	140	6298	3884 (10 d)
		$8.3x10^7 p/cm^2/s$ (60 MeV)	40.0 krad	142	6290	1299 (21 d)

Carrara, Charbon, *et al., ISSCC* 2009

MRI Compatibility

Time resolution in 9.4T

Delta FWHM < 10ps:

Test conditions:

- External laser source
- Internal TDC
- Integrated TDC

The Myth and the Challenges –

Some not-so-crazy ideas

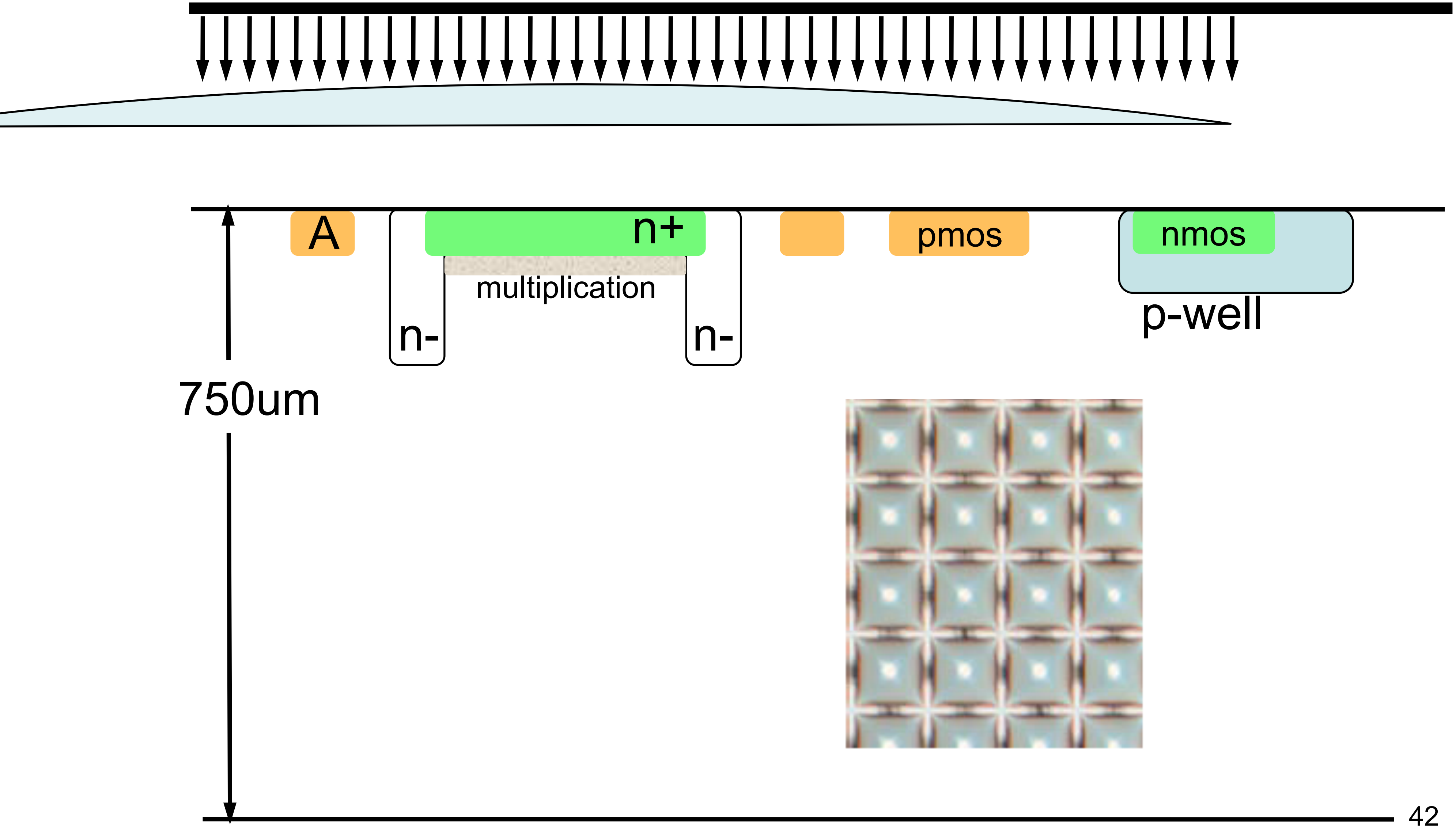
Demystifying

- SPADs miss lots of photons
- Time resolution limits
- Size limits
- Temperature and excess bias dependency
- Breakdown voltage variations

Important Trends in SPAD Imaging

- Sub-90nm CMOS
- (pseudo) 3D integration
- Backside illumination (BSI)
- Near IR
- Near and deep UV
- Soft and hard X-ray
- Larger formats

FSI Optical Concentration



Integrated Reflectors

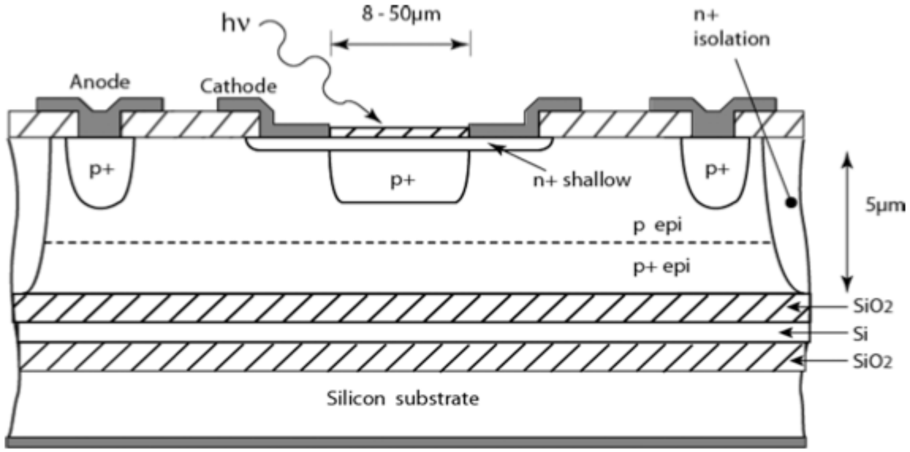


Fig. 1. Schematic cross section of the RCE SPAD detector.

M. Ghioni et al.,
IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 20, NO. 6, MARCH 15, 2008

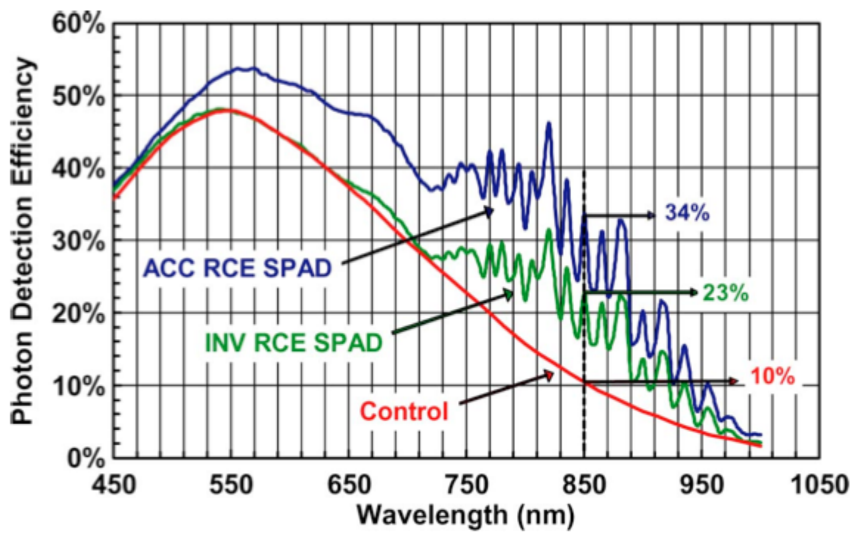
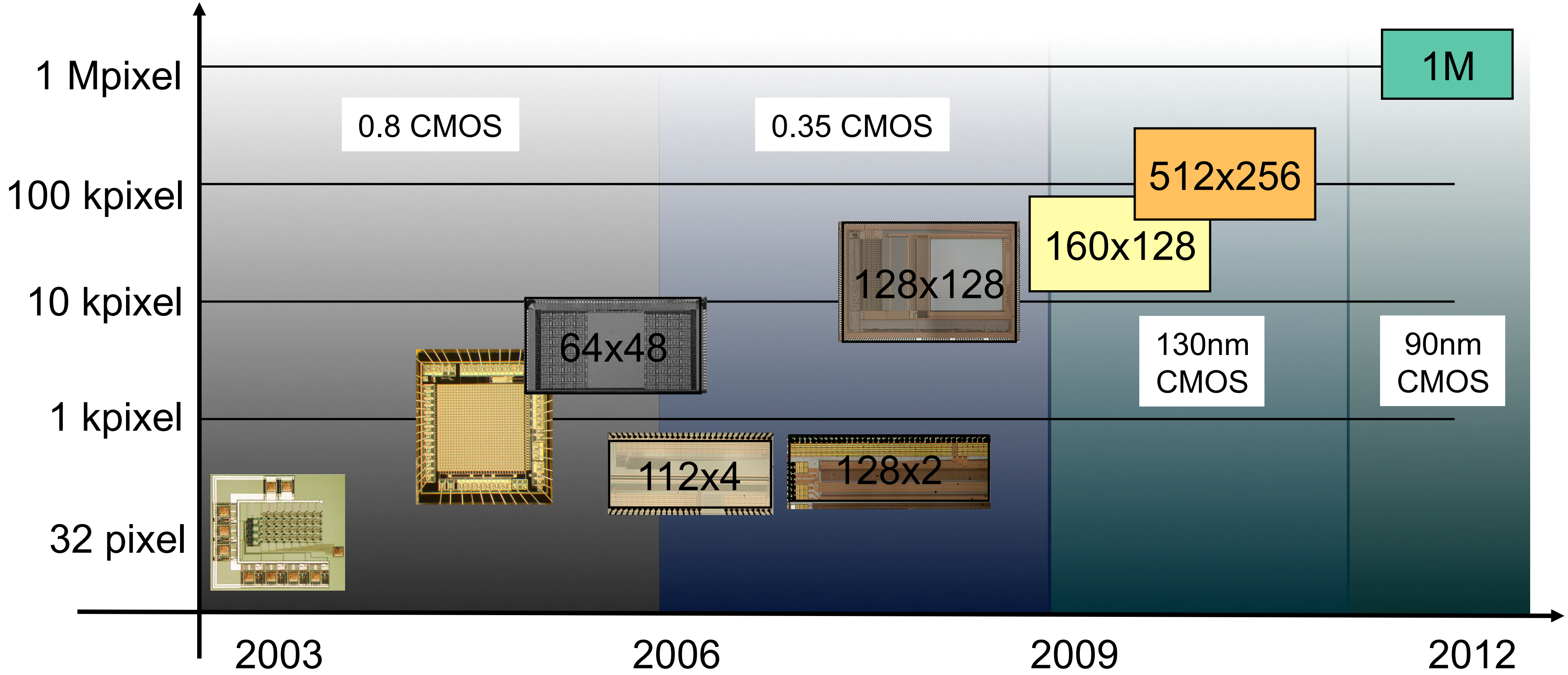


Fig. 2. PDE as a function of wavelength for control SPAD detector and RCE SPAD detector with INV or ACC layer formed at the Si–SiO_2 buried interface.

Moore's Law for Single-photon



Challenges Ahead

- Improve optical stack
- Increase fill factor
- Improve ***concentration*** techniques
- Increase functionality at no or little cost of performance
- Hunt for more applications
  - Space
  - Medical
  - Media/entertainment

Conclusions

- Single-photon imagers are here to stay
- New and old apps enabled
- Next challenges
  - More miniaturization
  - More parallelization
  - More flexibility
  - Novel imaging paradigms

Acknowledgements