Keynote : SIGNAL 2016

High Speed Image sensors

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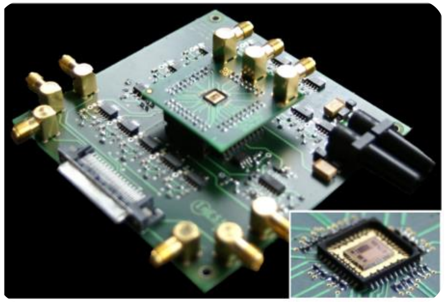
Outline

- Just history, a state of the art and future …



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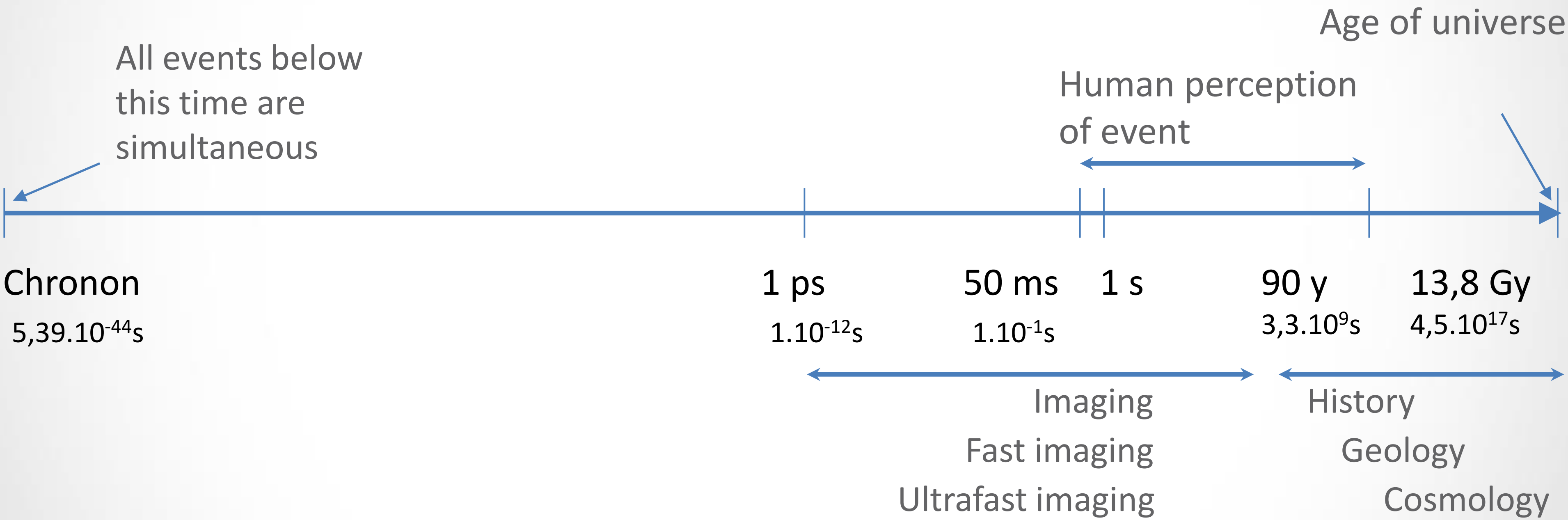
The time scale and the human perception of event



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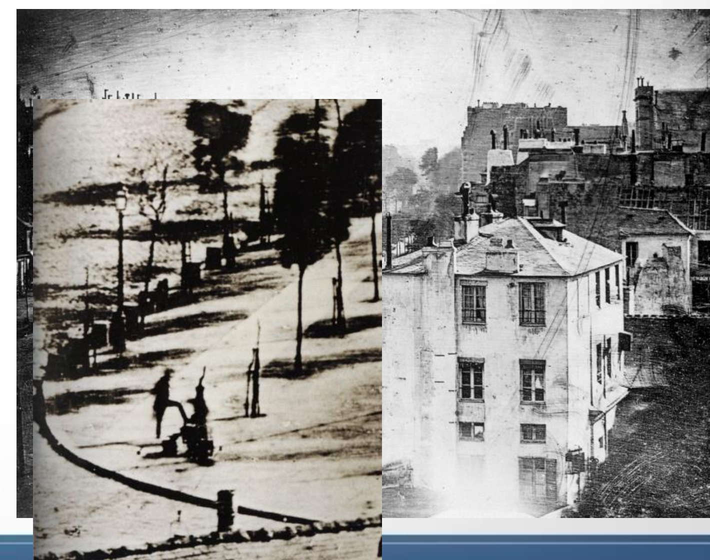
19th century - Fathers of Photography

- **1826 - Joseph Niépce**
  - Plate coated with Judea bitumen
  - Mean exposure time **10 hours**

Fig. I. 1: "Point de vue du Gras", 1826. Earliest surviving photograph taken by Niépce.

- **1838 - Louis Daguerre**
  - Silver plate exposed to chemical vapor
  - latent image that has to be « fixed »
  - Daguerréotype
  - Mean exposure time **30 min**
  - **French government bought the invention and give it to the world**



Boulevard du temple - Paris

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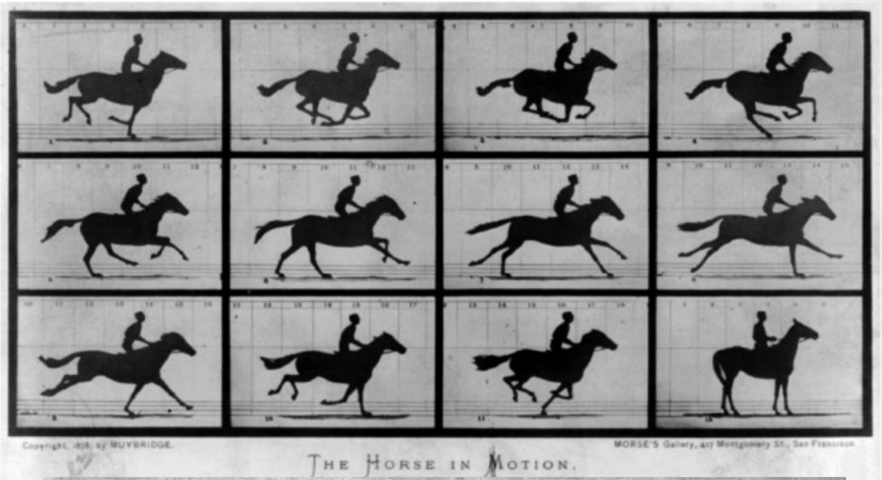
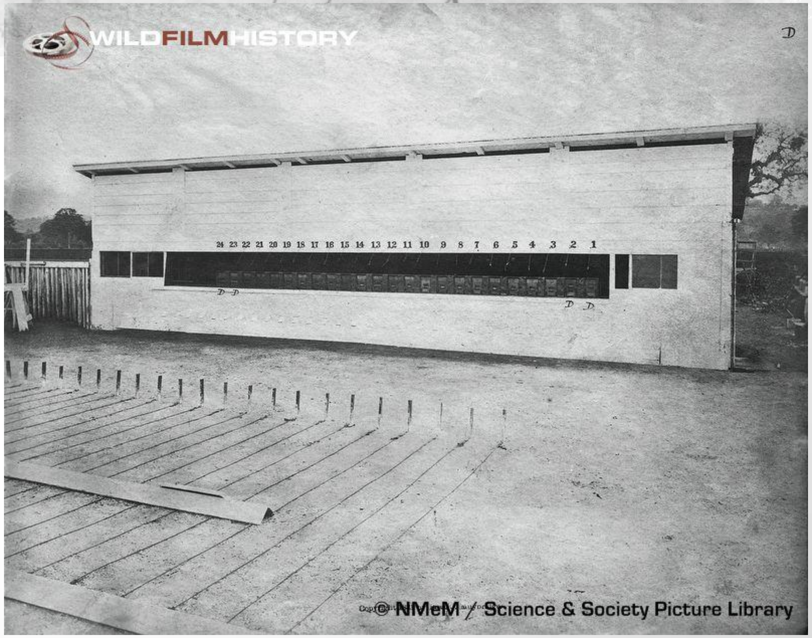
19th – Birth of High speed photography

- **1878 Eadweard Muybridge**
  - Use of *collodion* ➔ allows short fast exposure time but have to be used before It get dry
  - Mean exposure time **500µs**
  - **Use 24 different cameras triggered by a string**

➔ Only 24 frames





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20th century – first real high speed camera

- 1926: two high speed camera systems

British Heape-Gryll

- 4 tonnes, 8 horsepower
- 5000 frames per second
- Film drum

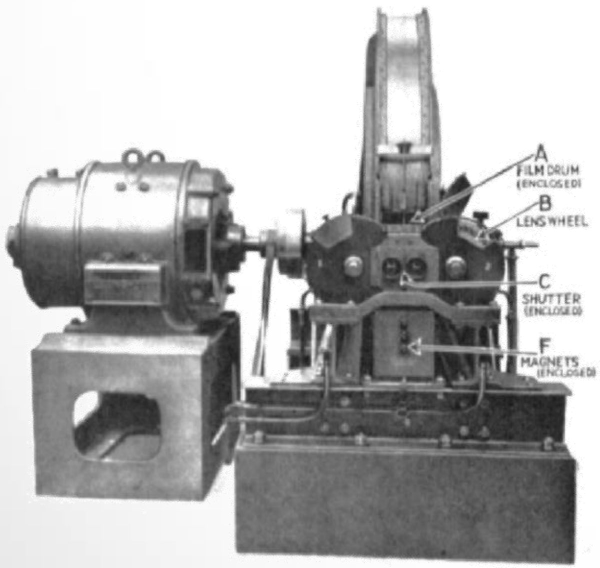
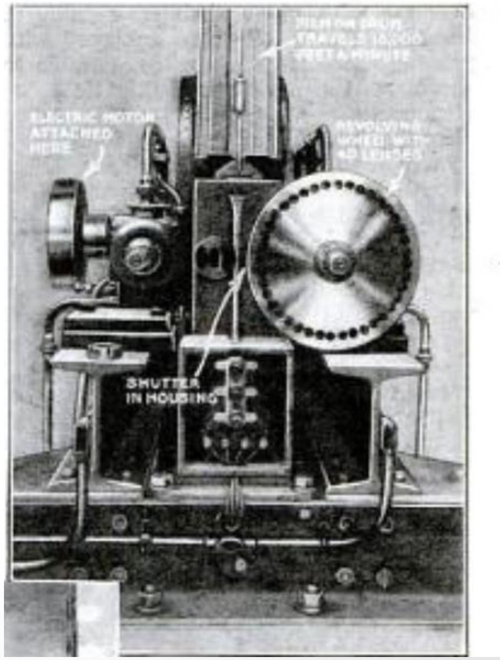


Fig. I. 6: Photograph of the Heape and Gryll's Machine for High-speed Photography [Hea26].

American Francis Jenkins



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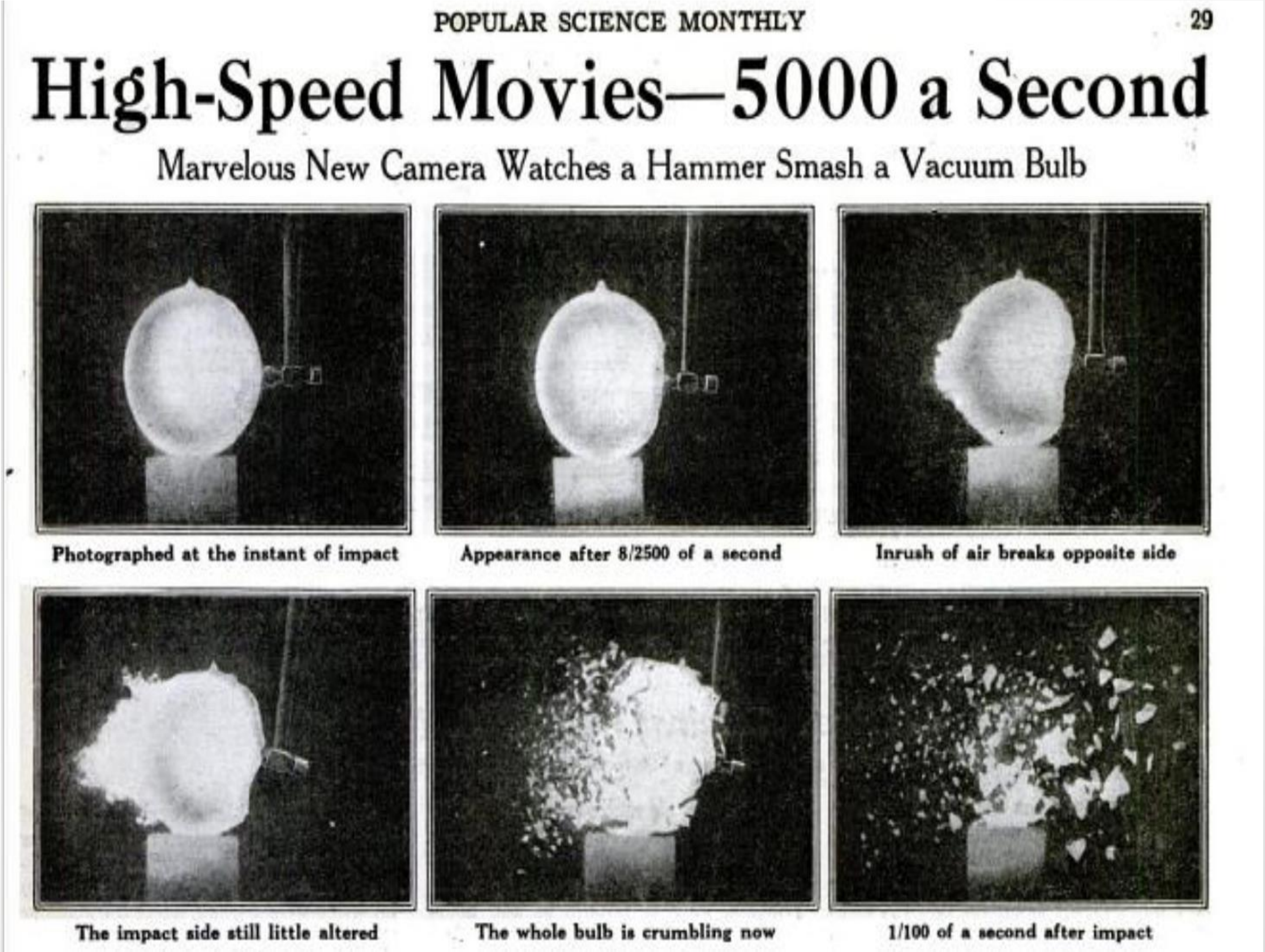
20th - popular science October 1926



POPULAR SCIENCE MONTHLY 29

High-Speed Movies—5000 a Second

Marvelous New Camera Watches a Hammer Smash a Vacuum Bulb

Photographed at the instant of impact

Appearance after 8/2500 of a second

Inrush of air breaks opposite side

The impact side still little altered

The whole bulb is crumbling now

1/100 of a second after impact

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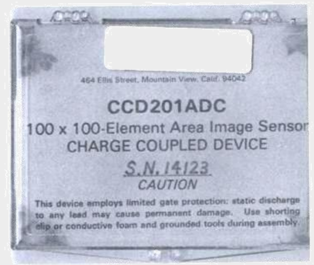
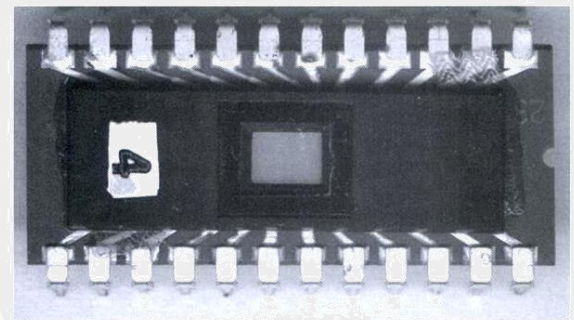
20th – Digital high speed video

- 1973, Fairchild first CCD image sensor (100x100)





- 1991 KODAK EKTAPRO Motion Analyzer 4540
  - First digital high speed video camera
  - Frame rate
    - **4500** fps (256 x 256 Pixel),
    - **40500** fps (64 x 64 Pixel)
  - max. frames 1024
  - Resolution 256 x 256 Pixel
  - Grey levels 256

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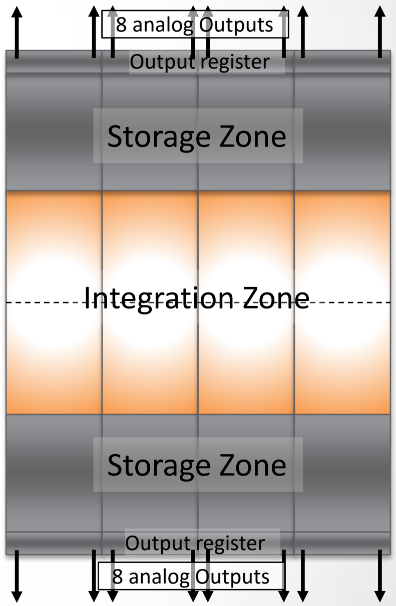
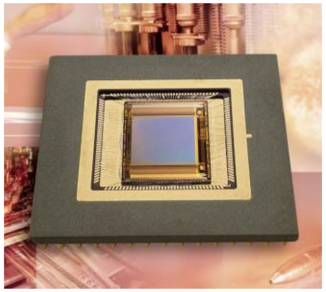
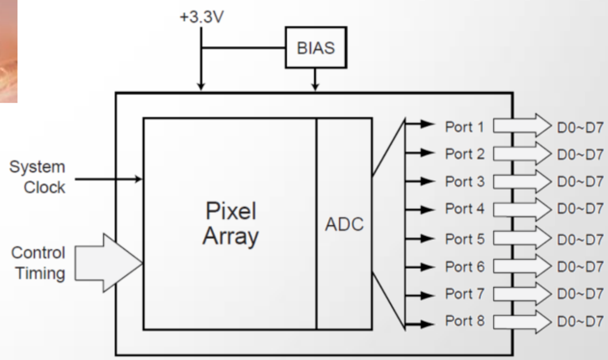
2000 – The CMOS revolution

- 2000, ICube lab designed camrecord 1000 fps @ 512x512
  - 16 outputs frame transfer CCD sensor
  - ➔ 16 external ADCs and 256MB memory
  - ➔ Time to Design the camera : **3 years**



- Meanwhile, **CMOS** sensors for high speed imaging appeared
  - **PB1024** Photobit (E.Fossum)
  - 500 fps @ 1024x1024
  - 1024 column 8 bits ADCs
  - 528 Mbytes/s (8x8bitx66MHZ)
  - ➔ Time to design the camera : **5 months**





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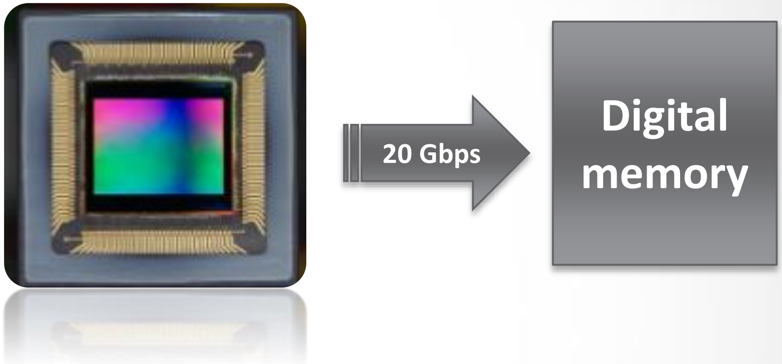
Current High speed video sensor

Optical format	4/3”
Active resolution	2368 x 1728 pixels
Pixel	7um pitch PPD global shutter pixel
Full well	20,000e- in 5T; 45,000e- in 3T mode
Read Noise	22e- (AM41V4) 18e- (AM41V4ZC)
Responsivity @ 550nm	8V/Lux-s (AM41V4) 11V/Lux-s (AM41V4ZC)
Conversion gain	70 uV/e- (AM41V4) 95uV/e- (AM41V4ZC)
Nominal Frame Rate	500 Frames/s @ full resolution
Maximum Frame Rate	700 Frames/s, 7-b ADC performance
Column ADC	10b
Data Output	16 ports @ 10b wide per port, CMOS 1.8V



- LUXIMA AM41
- 2 Gpixel/s
- 1 column ADC
- 20 Gb/s

800x600px, 1276fps, 1/3003s

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21th - Current High speed video

- State of the art high speed video camera
  - **Phantom v2511**,
    - 25kfps @ 1280 x 800
    - 1,000,000 @ 128 x 16
    - Record time : 96 GB filled in 2.6 second

  - The limit of conventional high speed video is due to I/O chip max speed
    - 25 Gpixel/s, 12 bits → 300 Gb/s !!
    - Present **fastest** commercial single-**laser**-single-fiber **network connections** max out at just **100Gbps**, 4 wavelengths at 25Gbps

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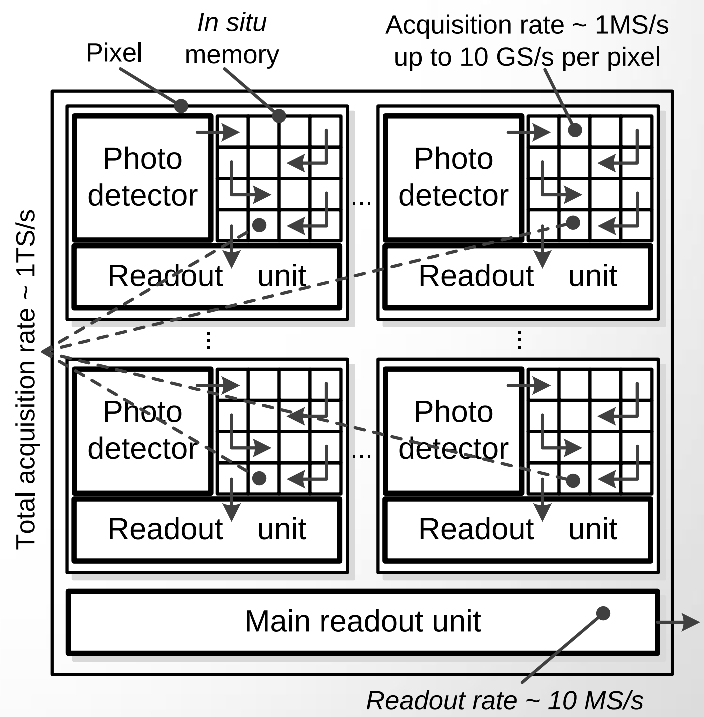
21th - Ultrahigh Speed solid state camera

- **How to overcome the limit of the sensor I/O speed ?**

Keep the data in the sensor ! ;-)

- Concept introduce by Elloumi In 1994
- Acquire the scene in a burst of images stored inside the pixel
- Readout the sequence of images at a conventional data rate



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Burst imaging concept

- Continuous Imaging
- Burst Imaging

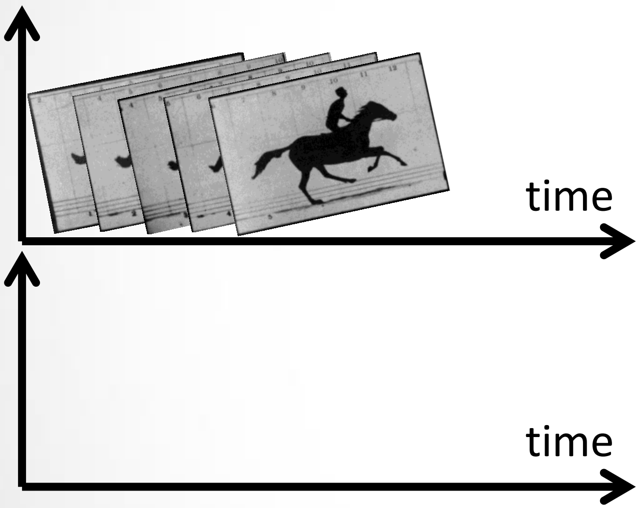
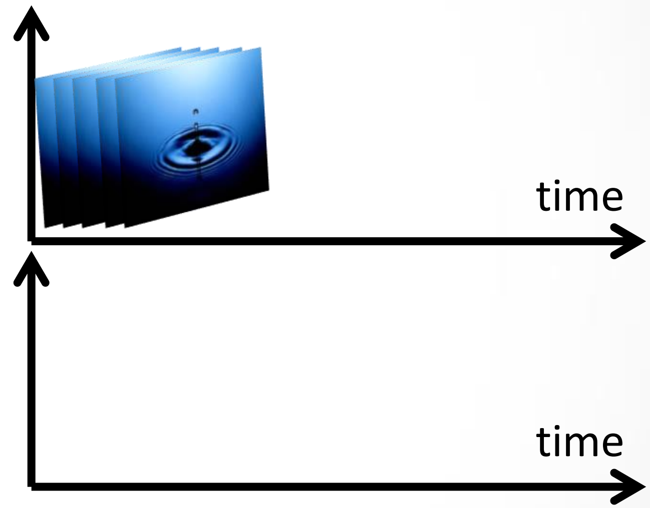


Image Acquisition

Image Readout



Up to 25 kfps @ 1 Mpix
→ up to 25 Gpix/s

100 kfps up to 1 Gfps
→ up to ~ Tpix/s

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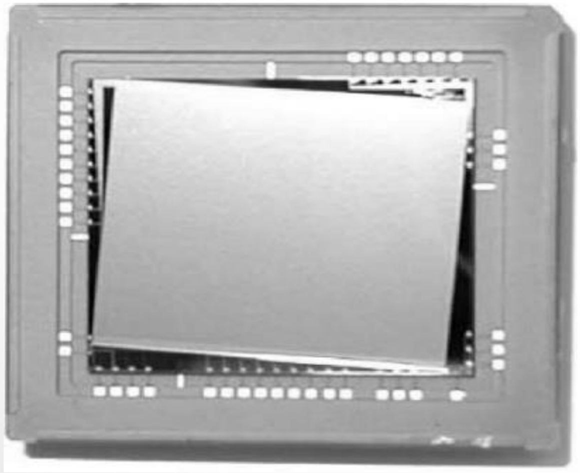
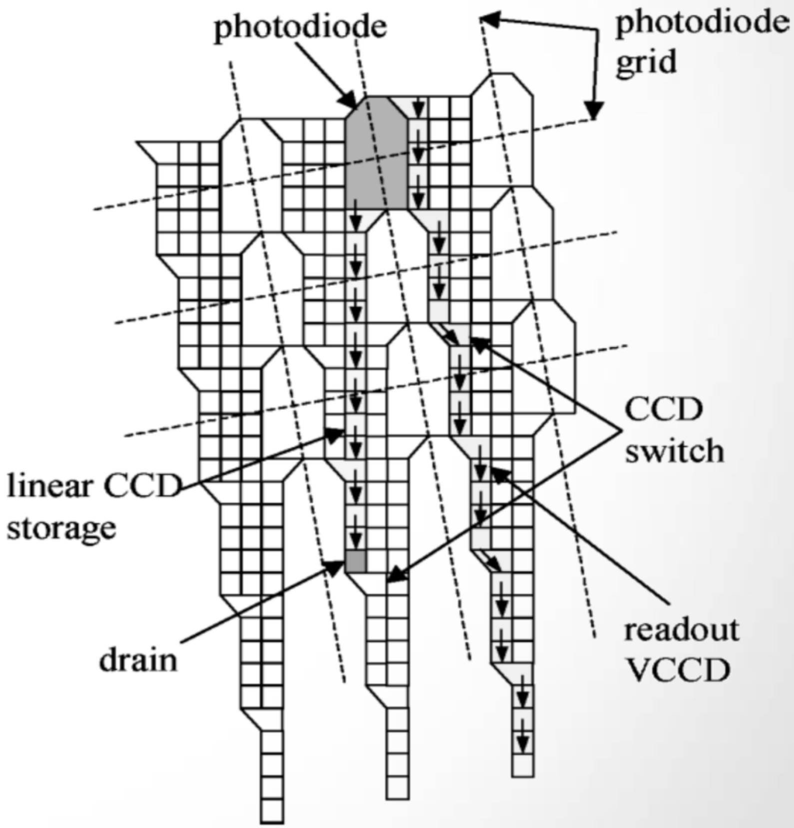
21th - Ultrahigh speed solid state camera

- **CCD technology** (by Etoh)
  - 1999
  - 1 Mfps, 100k pixels
  - 100 frames
- Speed limited by CCD transfer efficiency





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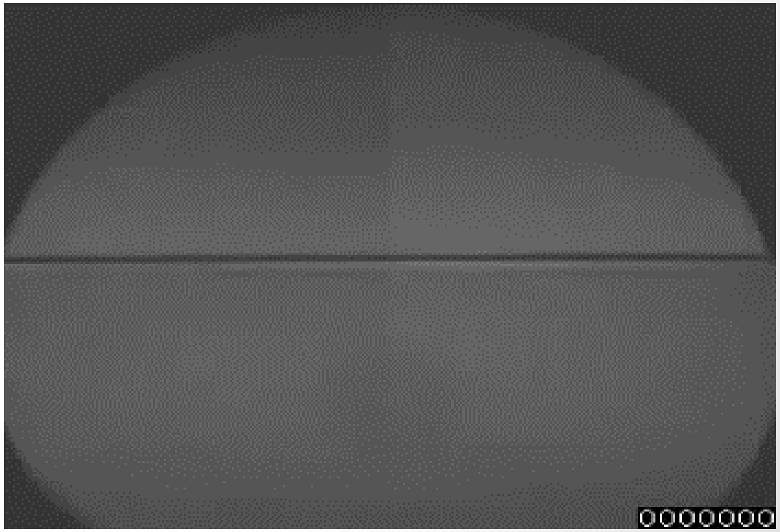
21th - Ultrahigh speed solid state camera

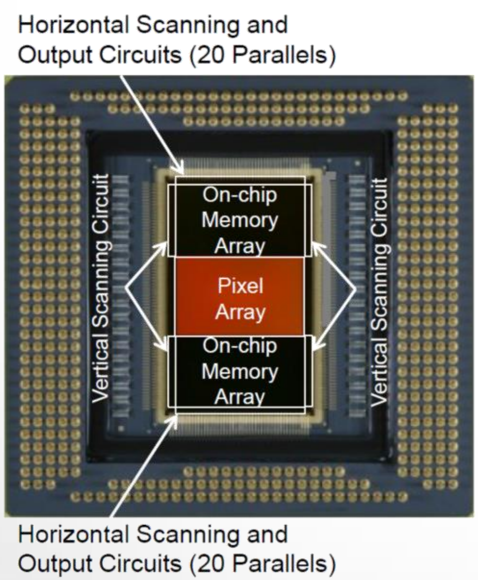
- Shimadzu
  - Model HyperVision HPV-2
  - 312x 260
  - 100 frames
  - Up to 1 Mfps
  - Acq. rate 81 Gpixel/s

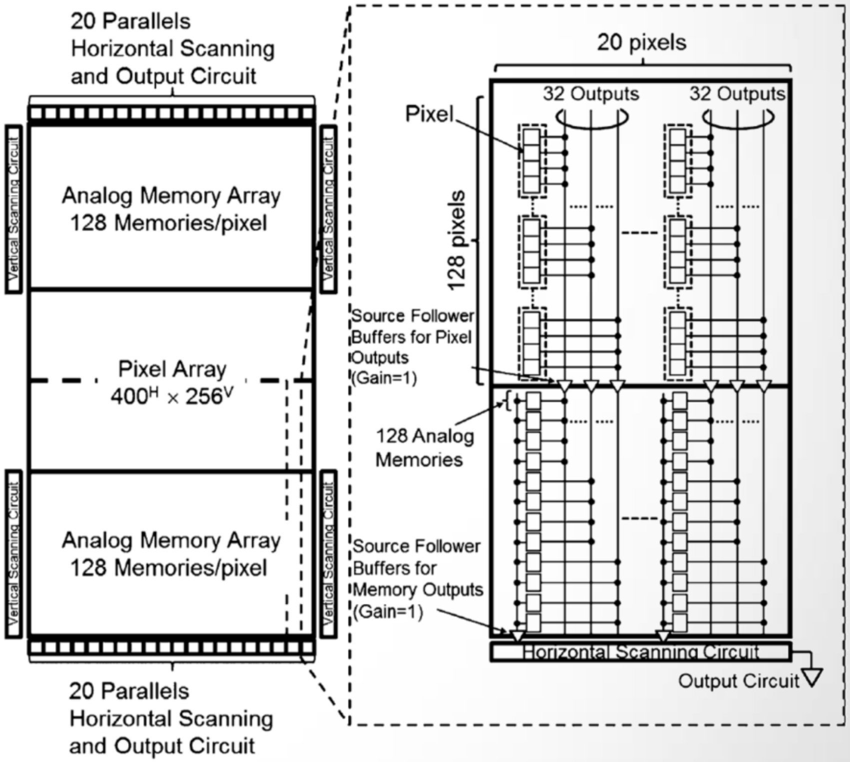


Shock wave from an explosive exploding underwater (Recording speed: 1,000,000 fps)

21th - Ultrahigh speed solid state camera

- **CMOS Technology** (by Sugawa)
- 2013, 180 nm
- Up to 20 Mfps, 100k pixels
- 128 frames
- CMOS cap memories
- Good fill factor 37%





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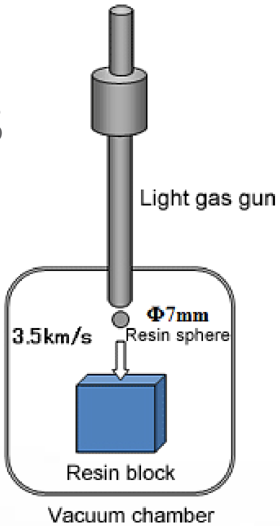
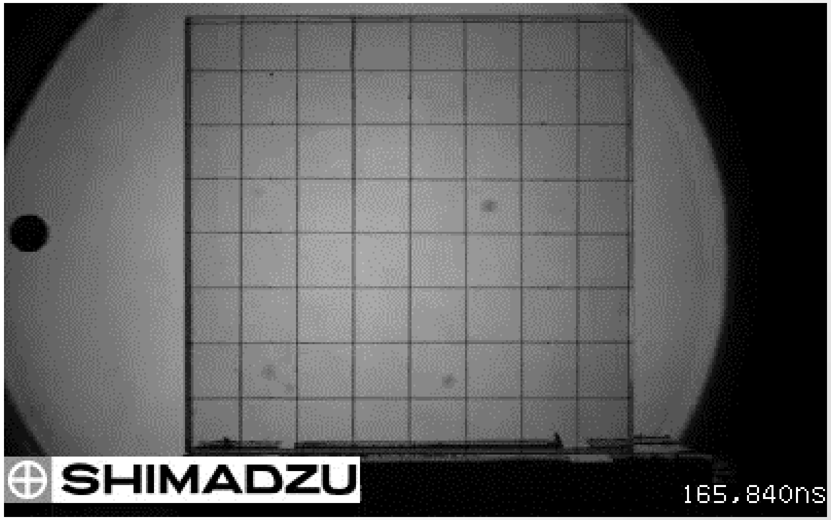
21th - Ultrahigh speed solid state camera

- Shimadzu
  - Model HyperVision HPV-X
  - 400 x 250
  - 128 frames
  - 10 Mfps
  - Acq. rate 1 Tpixel/s





High-Speed Collision of Resin Sphere
Recording Speed: 2 million frames/s

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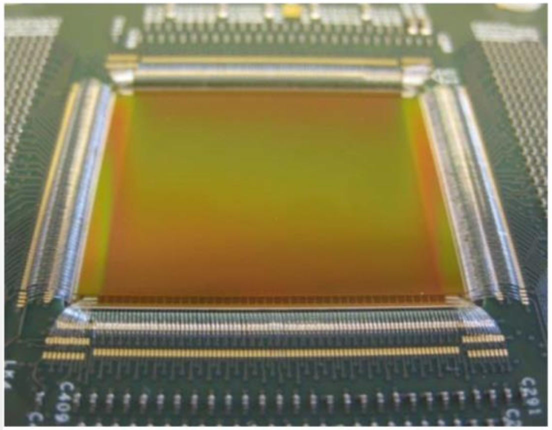
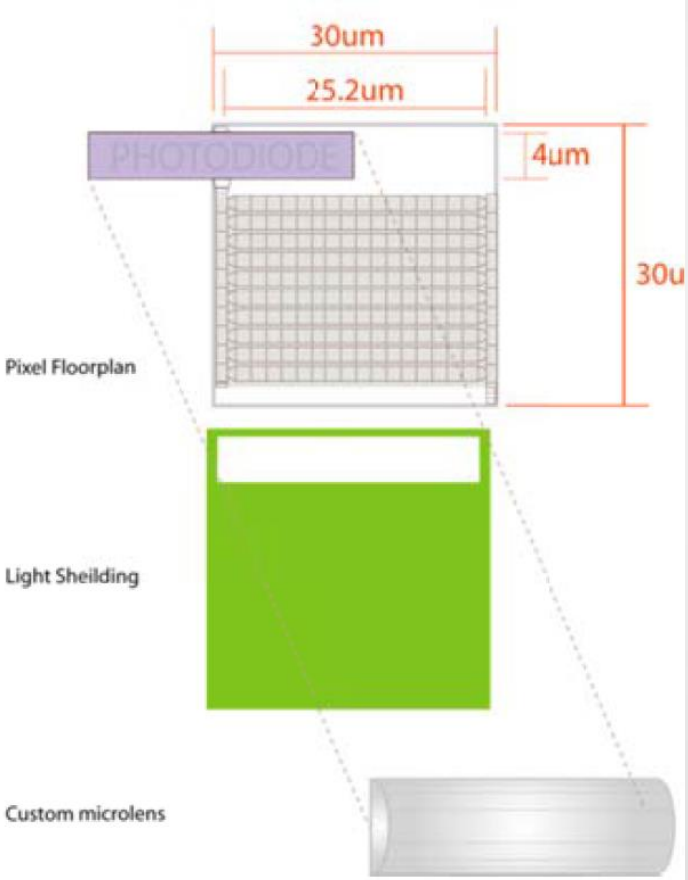
21th - Ultrahigh speed solid state camera

- **Hybride CMOS-CCD Technology** (by Crooks)
- 2013, 180 nm
- Buried Channel CCD
- 5 Mfps, 700k pixels
- 180 frames
- Fill factor 11%





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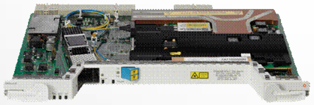
21th - Ultrahigh speed solid state camera

- Specialised-imaging
  - Model Kirana
  - 924 x 768pixel - 180 frames
  - 5 Mfps
  - Acquisition rate : 3.5 Tpixel/s
  - 10 bits

  ➔ 35 Tbit/s

350 modules of the **100 Gbps** fastest commercial **laser** network **connections** should be required to **extract the data** from the sensor in **real time**



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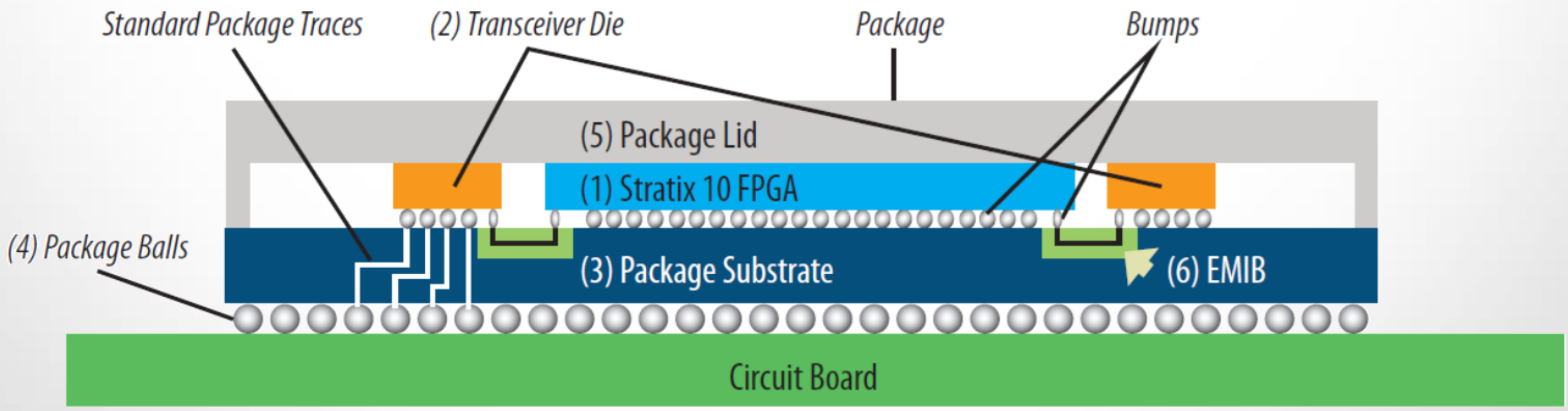
Toward digital ultra high speed video

- 2.5D and 3D microelectronic
  - Silicon interposer Or Intel Embedded Multi-Die Interconnect Bridge (EMIB)
  - Ultra high density and short distance interconnect
    - Fast I/O realized by dedicated high speed transceiver Die



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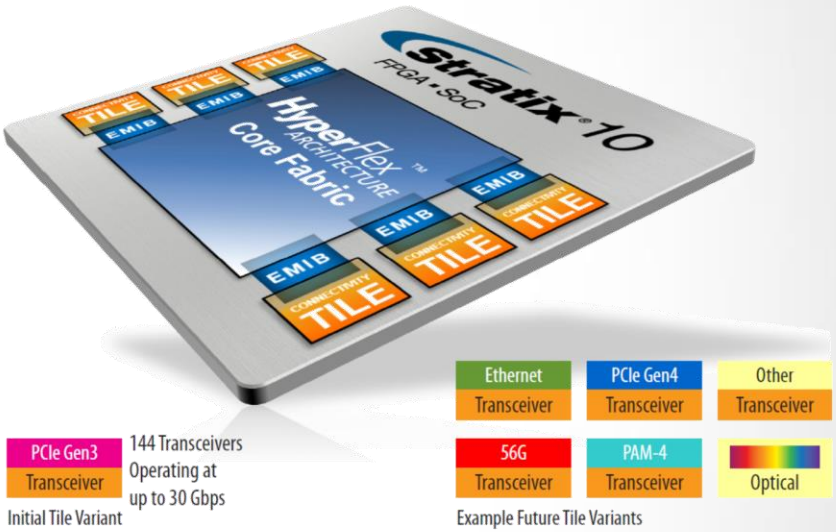
Toward digital ultra high speed video

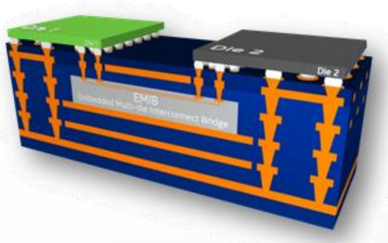
- State of the art
  - I/O interconnect
    - 144 x 30 or 17.4 Gbps

    ➔4 Tbps
    - Next generation
      - 56 Gbps or Optical

      ➔ 8 Tbps
  - High speed RAM interface
    - 10x discrete DRAM
    - 40 Tbps ??

➔Digital ultra high speed video is no more an unreachable dream





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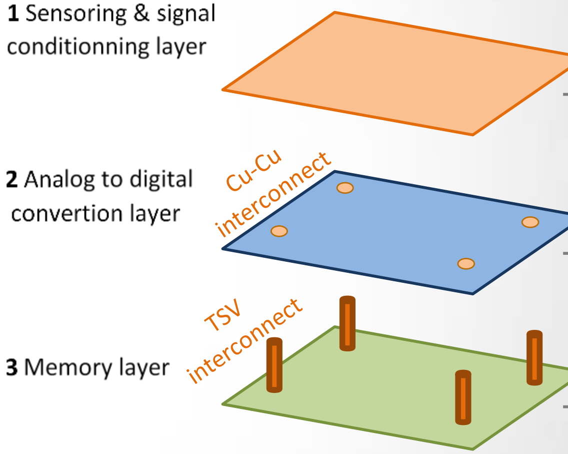
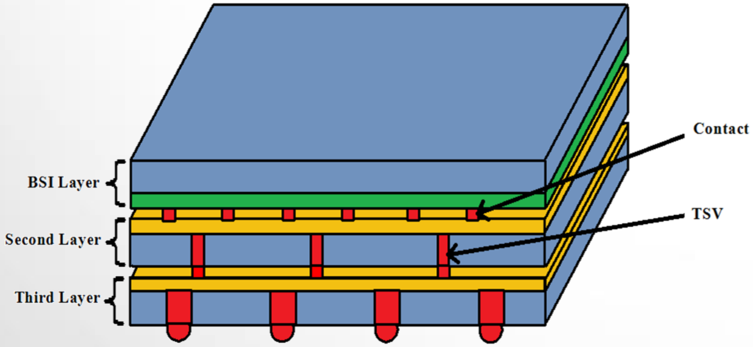
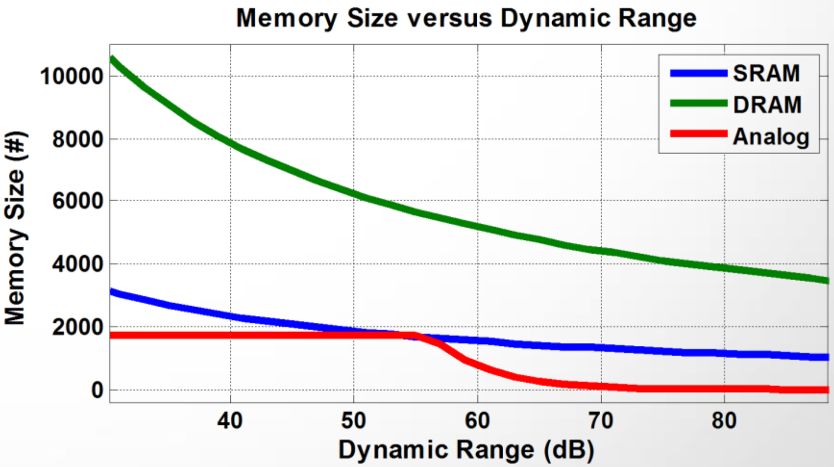
Toward digital ultra high speed video

3D Microelectronic Ultra fast BIS

- High sensitivity, low noise, low power and high speed pixels
- High speed, low power and low area ADCs
- High throughput and **high density** digital memory (28nm)







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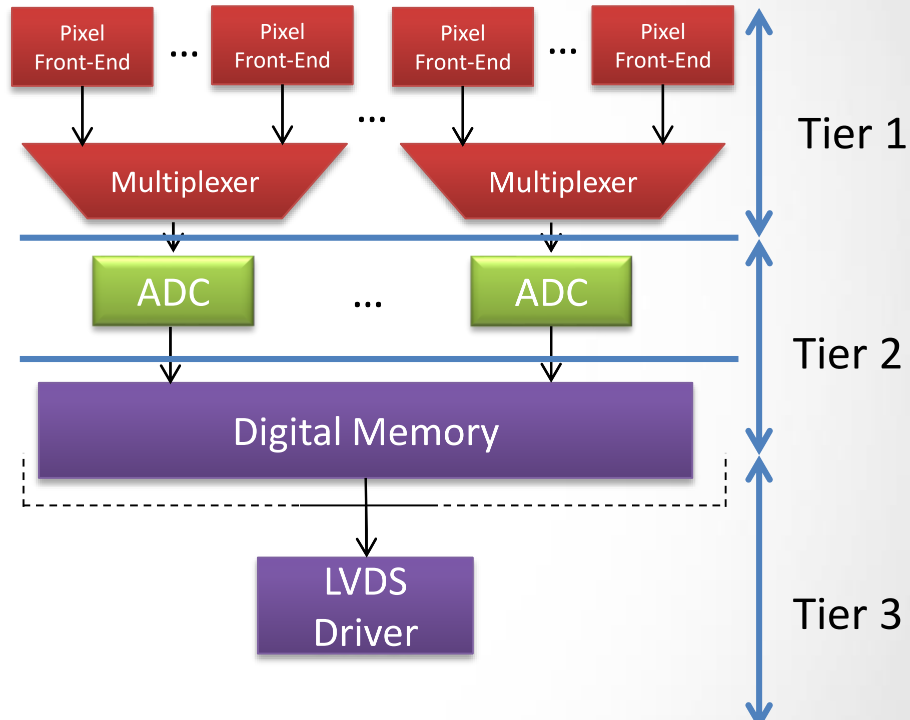
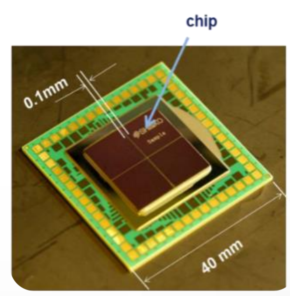
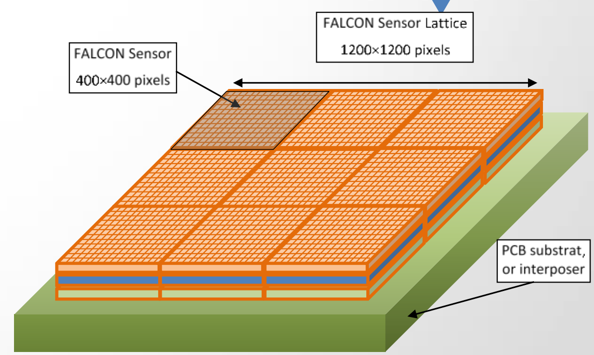
Toward digital ultra high speed video

- Main characteristics of the FALCON BIS
  - **10 Millions fps @ full resolution (400x400)**
  - Up to **100 million frames** per second (spatial resolution reduction and binning)
  - **Real** total acquisition rate > **10 Tera bits/s**
  - Digital storage and readout
  - High memory depth > **1000 frames**
  - Resolution heightening by lattice sensors (multiple of **400x400** pixels pixel pitch 50 µm)
- Architecture
  - Cluster of pixel sharing a ADC
  - Transimpedance amplifier front end
  - 100 Mega Samples per second ADC
  - Group of cluster for memory organization

  But ADC limits the maximal frame rate at 100Mfps …







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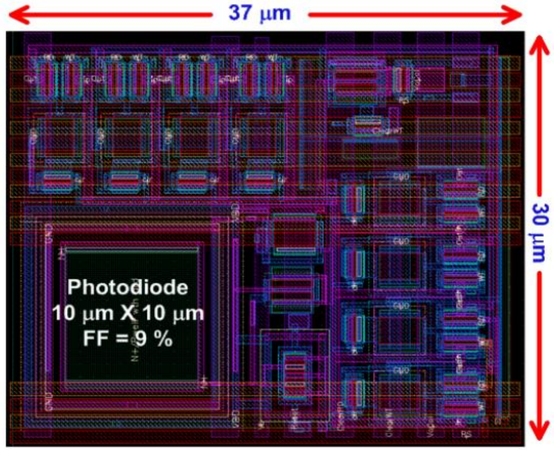
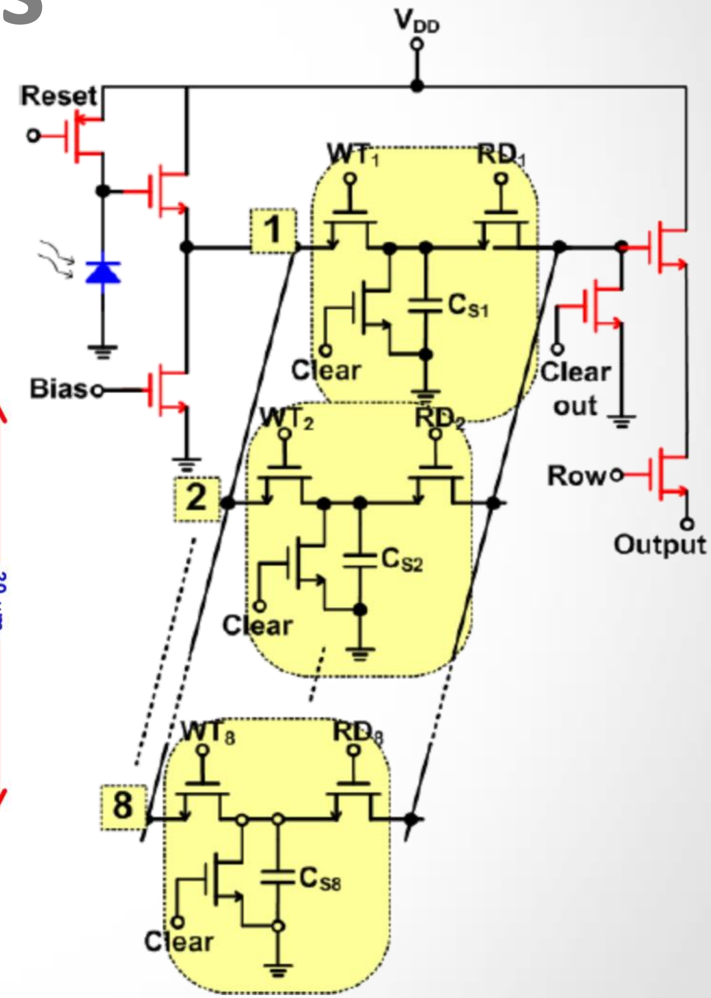
Torward to the GigaFps

- **CMOS** (by Deen)
  - 2009, 130 nm
  - Up to 1.3 Gfps, 32x32 pixels

but

  - Only 8 frames
  - Fill factor 9 %
  - No image





  - To much constraints
    - Spatial & temporal resolution

➔release the constraints …

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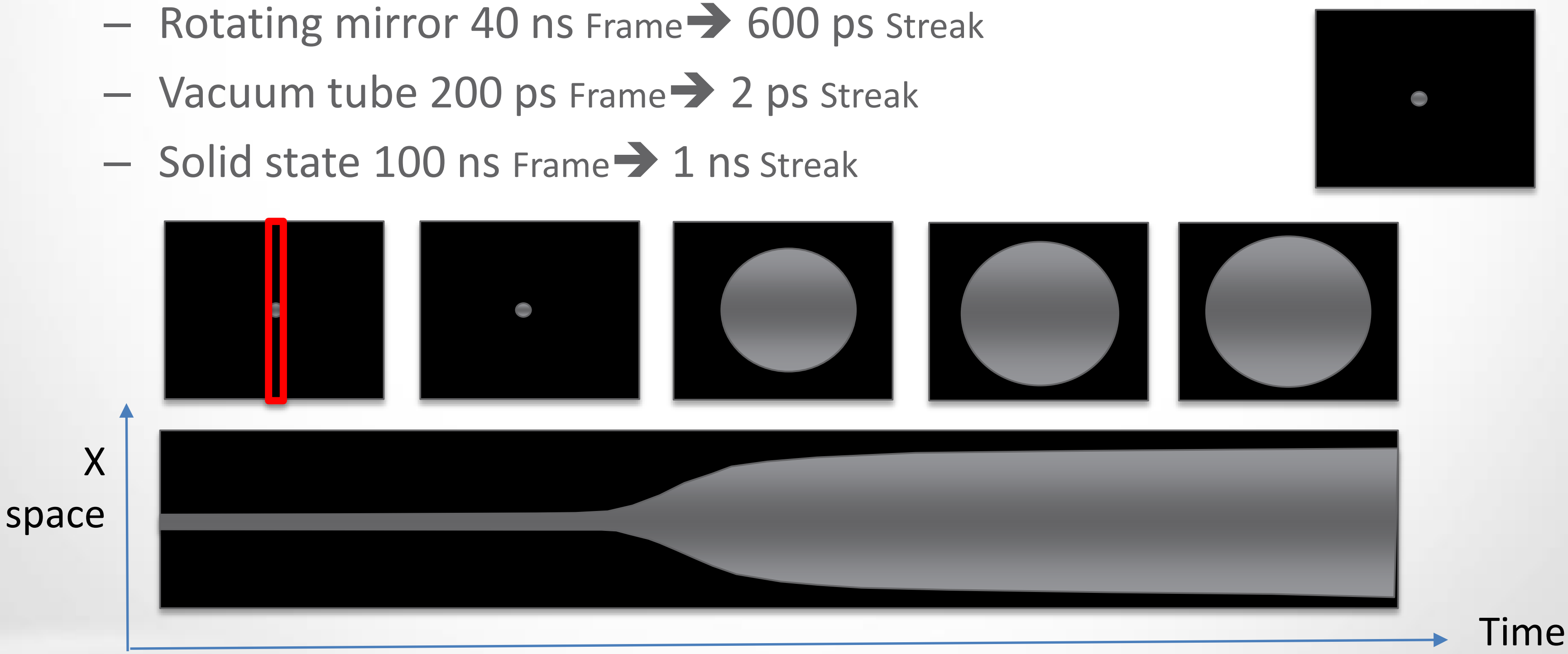
Streak Imaging

- Reducing the spatial resolution increase the frame rate
- Optimal speed obtain for one single column

➔Streak imaging

- About 100 times faster with whatever the technology
  - Rotating mirror 40 ns Frame➔ 600 ps Streak
  - Vacuum tube 200 ps Frame➔ 2 ps Streak
  - Solid state 100 ns Frame➔ 1 ns Streak



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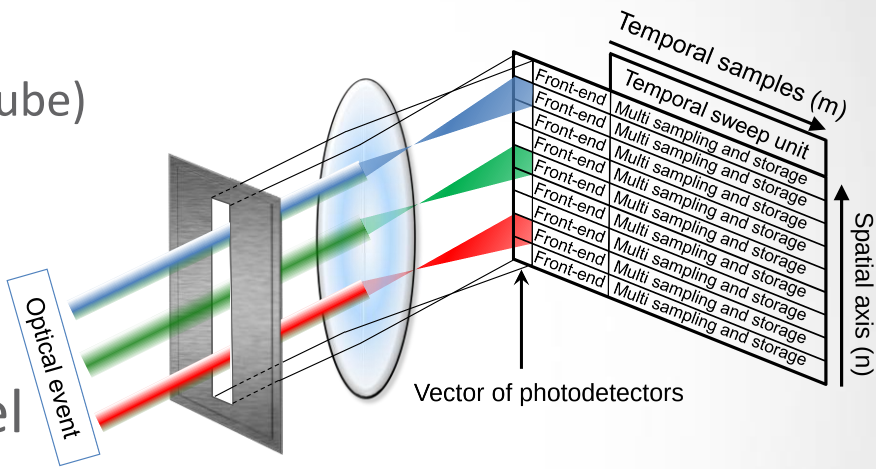
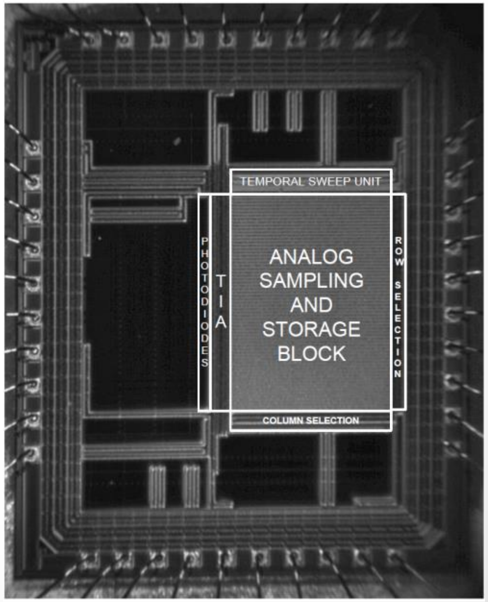
Toward to the GigaFps

- **CMOS Streak imaging**(by ICube)
  - 2013, 350 nm SiGe BiCMOS
  - Release of 2D Imaging contraints
    - Aera limited electronic for pixel pitch
  - Up to 8 Gfps, 128 frames
  - 64x1 pixels (streak imaging)
  - Pixel pitch 32 µm
  - Fill factor 84 %
  - Touching the physical limit of the technology
    - Single gate propagation time





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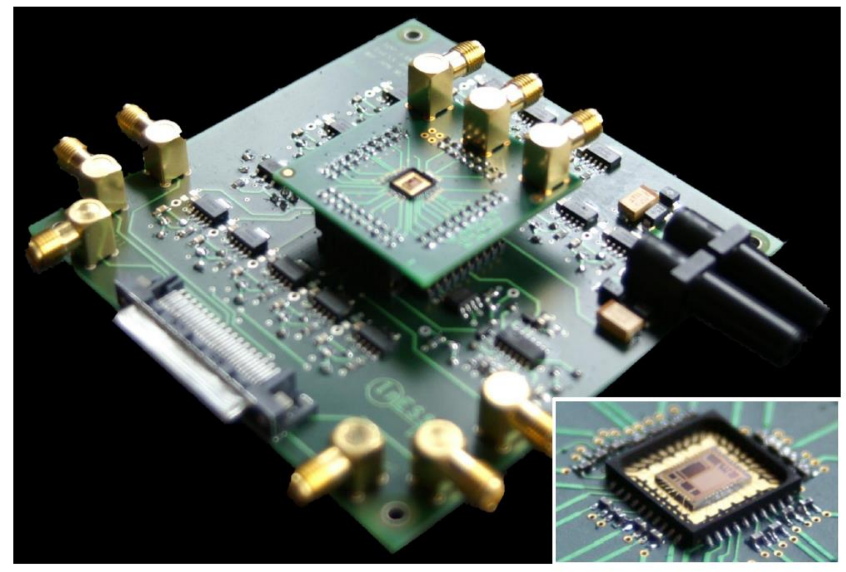
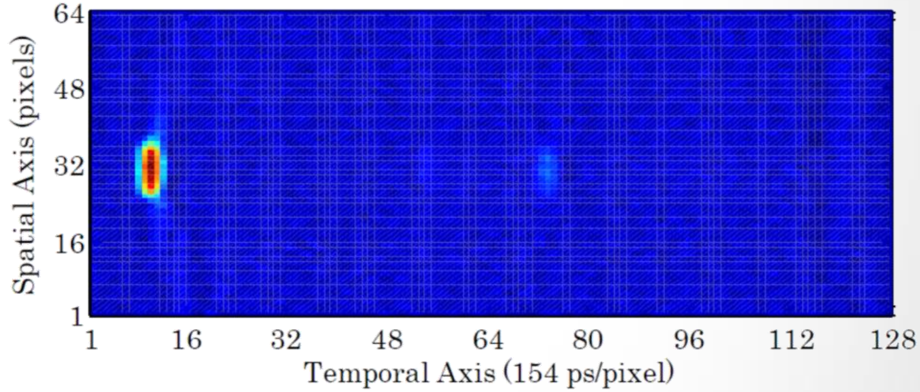
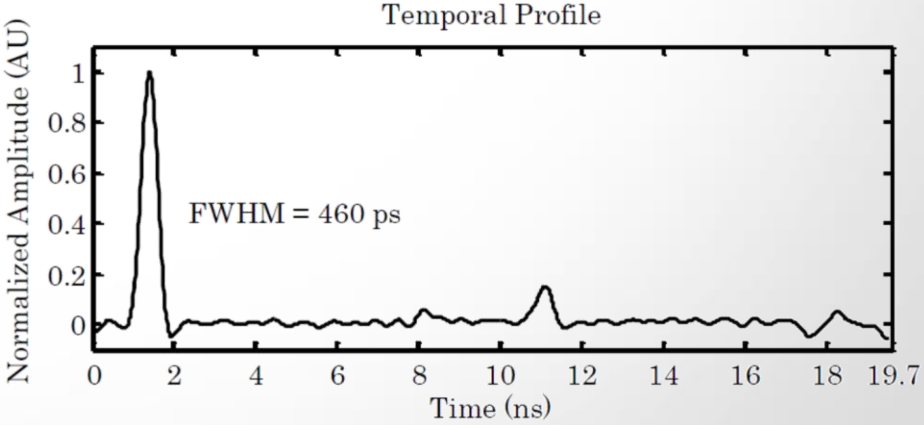
Toward to the GigaFps

- **CMOS Streak imaging** (by ICube)
  - subnanosecond temporal resolution
  - 100x faster than 2D Ultrafast image CMOS sensors







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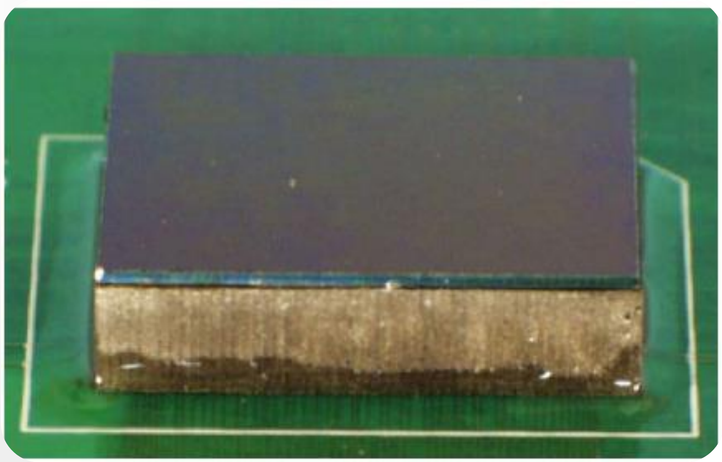
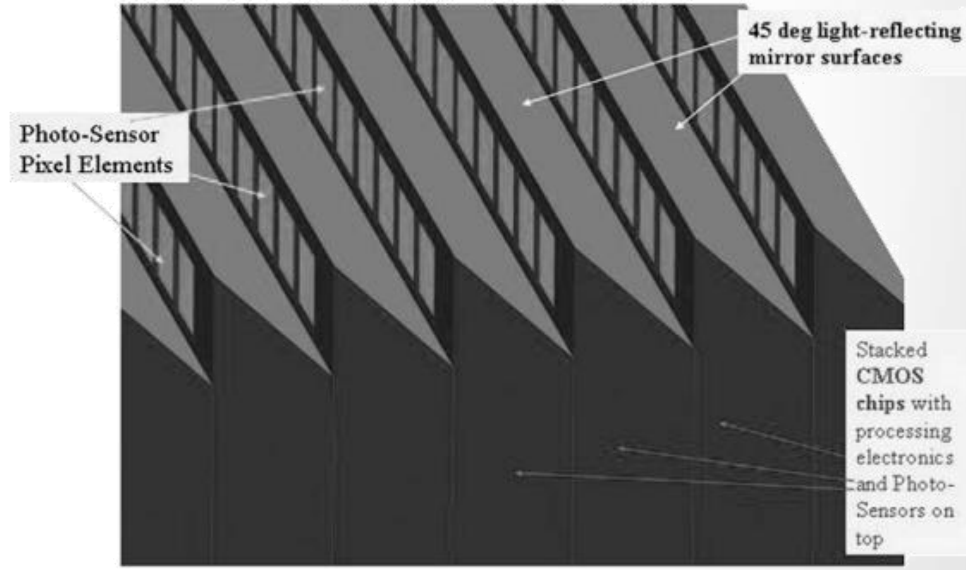
Torward to the Framing GigaFps

- **Streak imaging to frame imaging**
  – 3D microelectronic
  – Assembly of streak camera
  (Proposed by Kleinfelder)





➔ **The ultimate solid state video imager**

– 10 Gfps, up to 200 frames

– Does not exist for the moment …

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Single shot / repeatable event

- All previously described systems are single shot system
  - A **single** event is acquire
  - ➔Require the large data rate
- Many fast events are repeatable
  - Fluorescence, Tomography, LIDAR, Laser induce events …
  - The phenomenon can be sampled in several time

➔Require much less data rate

➔The temporal resolution can be highly increased

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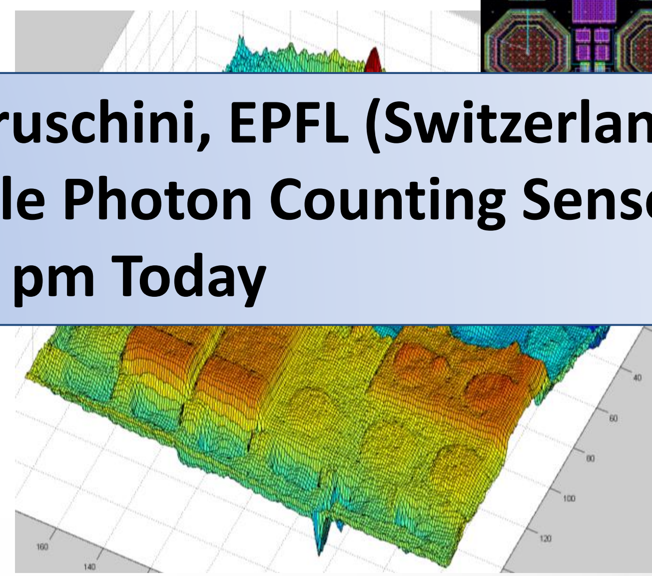
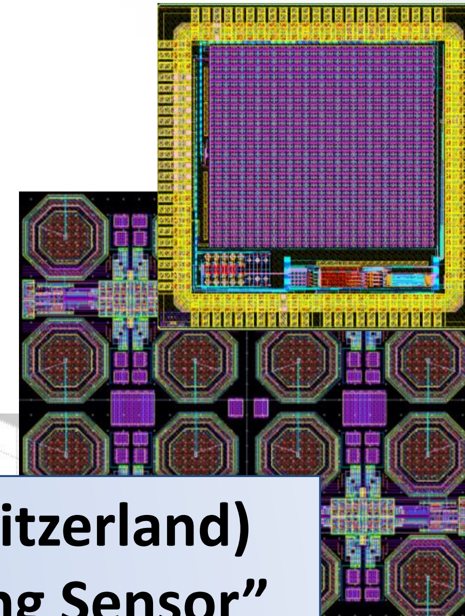
SPAD Sensors

- **Able to see the speed of light !**
  - 100 ps FWHM laser pulse propagating





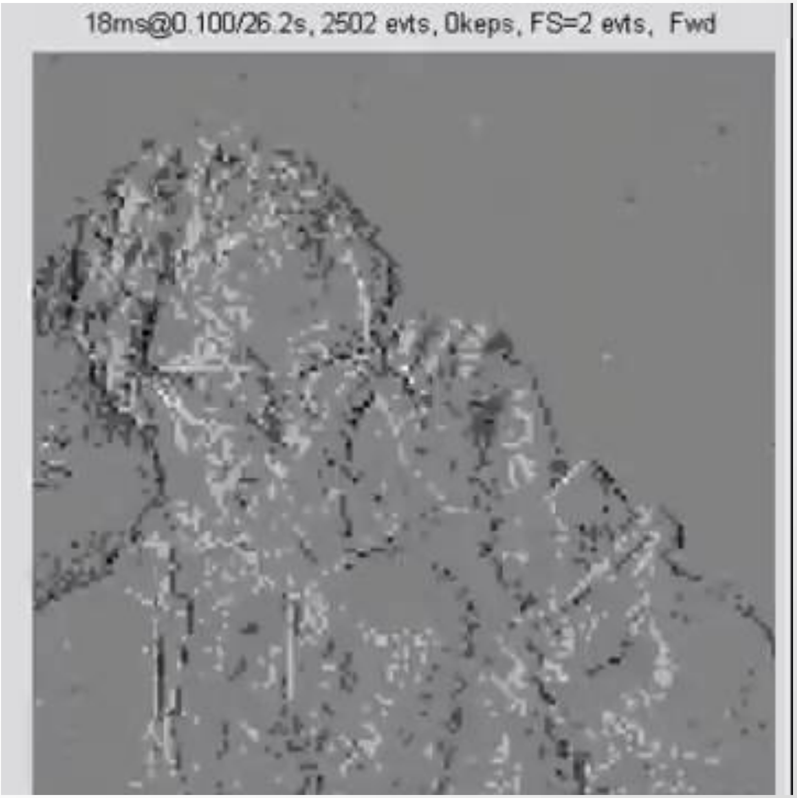
Keynote of Claudio Bruschini, EPFL (Switzerland)
“Time Correlated Single Photon Counting Sensor”
2:40 pm Today

Wilfried Uhring
Icube, University of Strasbourg and CNRS

Processing for increase video rate ?

- Low Level Data Processing
  - Remove unusefull information

Keynote of Laurent Fesquet, TIMA (France)
"Low-Power Event-driven Image Sensors"
1:45 pm Thursday

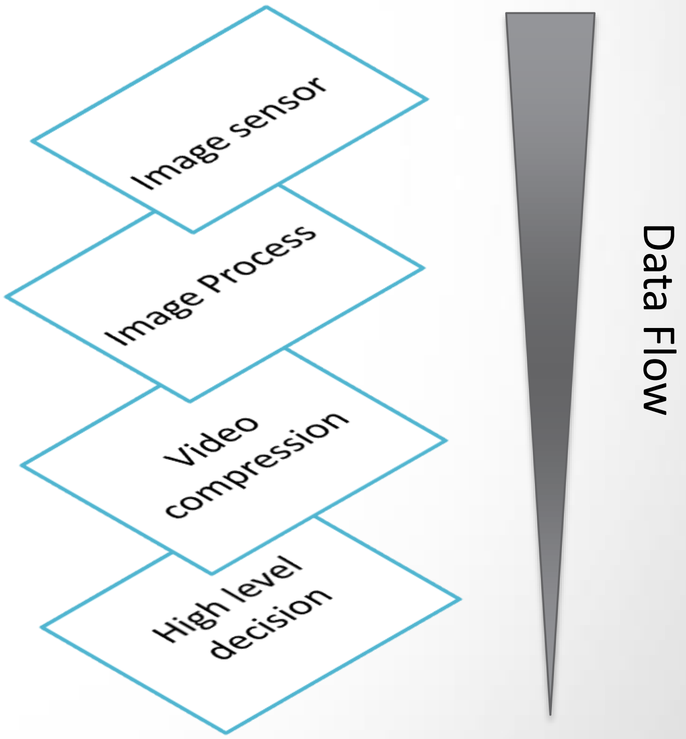


Wilfried Uhring
Icube, University of Strasbourg and CNRS

Processing for increase video rate ?

- High Level Data Processing
  - Embedded process
    - Extract only useful information

Keynote of Dietmar Fey, University of Elangen-Nürnberg
“Image Processing Application for Heteregenous Computing Architecture”
9:15 pm Thursday



Conclusion

- High speed imaging always push the technologies to their limits
  - Rotating mirror, Vaccum Tube and now solid state device
- **Digital High speed video**
  - 25 Gpixel/s with monolithic sensor (State of the art)
    - limited by I/O Speed
  - Up to 1 Tpixel/s with 3D microelectronic (Near Future)
    - limited by ADC
- **Analog High speed video** (Burst imaging with 100's frames)
  - CCD technology up to 100 Mega Frame/s
    - Limited by charge transfer process
  - CMOS technology up to 10 G Frame/s in combination with Streak imaging and 3D microelectronic
    - Limited by photodiode and frontend bandwidth (GHz range)
- Solid state ultrafast imaging is young and very promising …

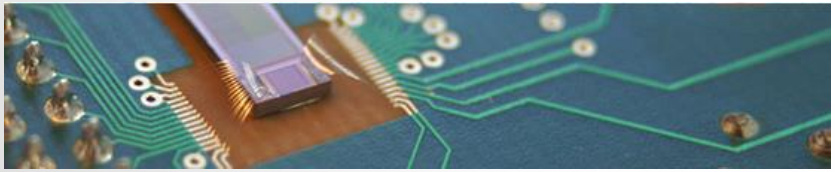
Wilfried Uhring
Icube, University of Strasbourg and CNRS

Contact

Pr. Wilfried Uhring

Strasbourg IHU SMIM (Systems and Microsystems for Medical Instrumentation) Team Leader

Icube SMH (Heterogeneous Systems and Microsystem) team member.



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