Hong Kong University of Science and Technology

Electronic and Computer Engineering Department

Low Power Sensors for Urban Water System Applications

Prof. Amine Bermak

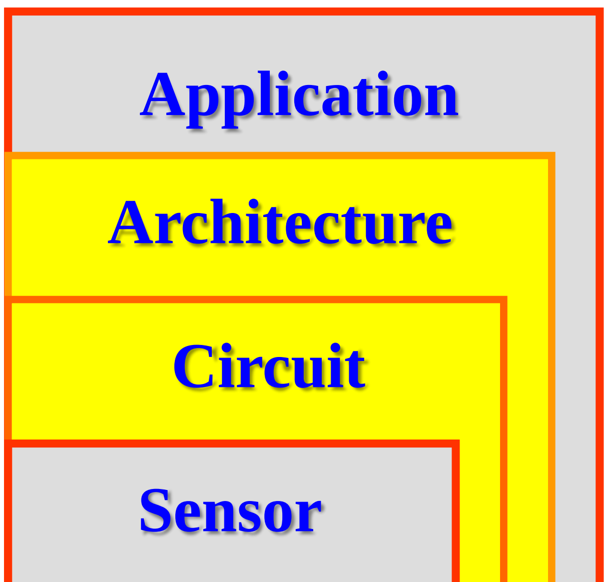
Workshop on “Smart Urban Water Systems” HKUST 2015

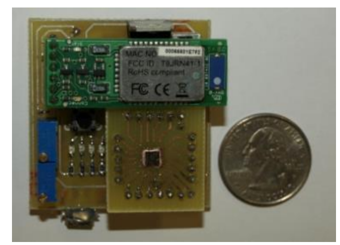
S2IS Smart Sensory Integrated Systems Lab

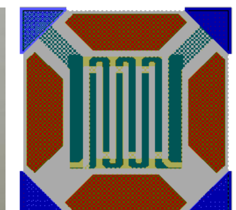
Smart Sensory Integrated Systems Lab

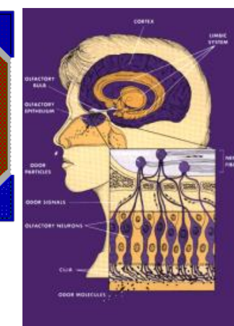
S2IS
Smart Sensory
Integrated Systems Lab

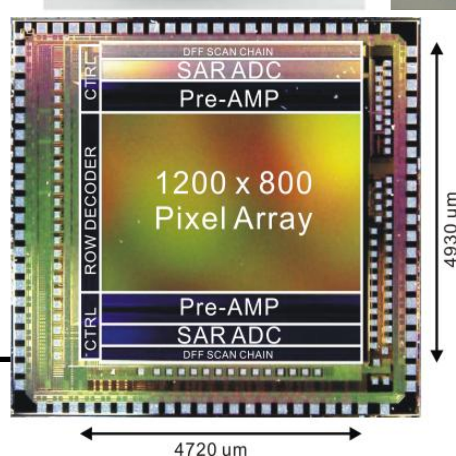
Architectural, material, and circuit level solutions for smart and low-cost Microsystems (sensors)

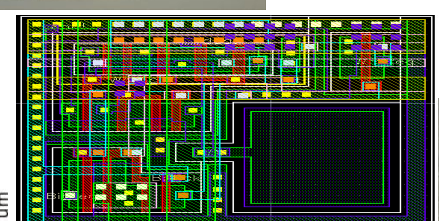


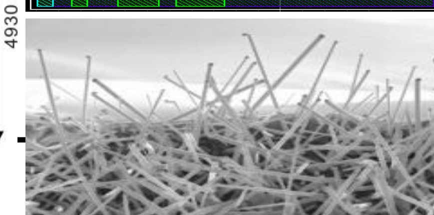


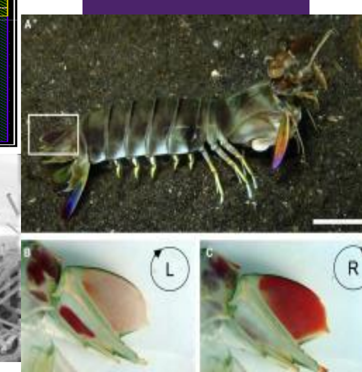












"Autonomous Intelligent Microsystems"

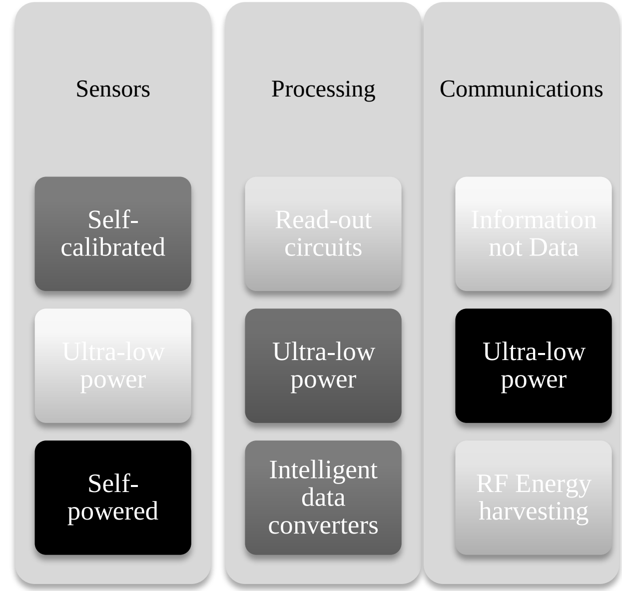
Autonomous integrated smart sensing systems capable of "sensing, processing and communicating"

- Wireless Sensing Platforms
  - RFID with sensors, wireless sensor Network (WSN) etc.

Sensors	Processing	Communications
Self-calibrated	Read-out circuits	Information not Data
Ultra-low power	Ultra-low power	Ultra-low power
Self-powered	Intelligent data converters	RF Energy harvesting

Challenges to be Addressed

Challenges in WSN

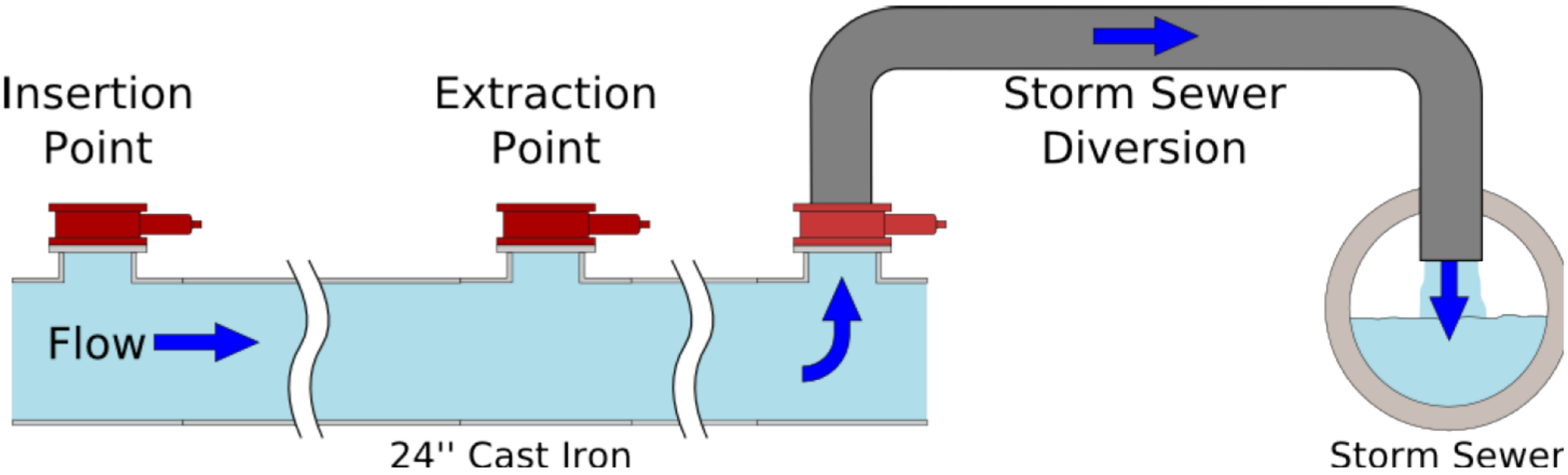


- 4 main challenging requirements in “install and Forget” Electronics
  - Requirement 1: Low-cost → Mainstream CMOS technology (system integration)
  - Requirement 2: Battery-less: replacement hinders massive deployment in remote locations, cost issue → Self-powered + ultra-low power operation
  - Requirement 3: No human intervention for maintenance → Self-calibration.
  - Requirement 4: Low-Power communication: Information rather than data communications → Intelligent converters & Compress before communication

Talk Agenda –Towards Autonomous sensors

- State-of-the-Art Water Pipe Sensing
- Time-Domain Imaging –Low power alternative
- Time-Domain Image Processing – Smart Vision Sensor
  - Compression, Histogram Equalization, Adaptive quantization
- Alternative ADCs: Analog-to-information AIC converters.
- Energy harvesting Image Sensors
- Conclusion

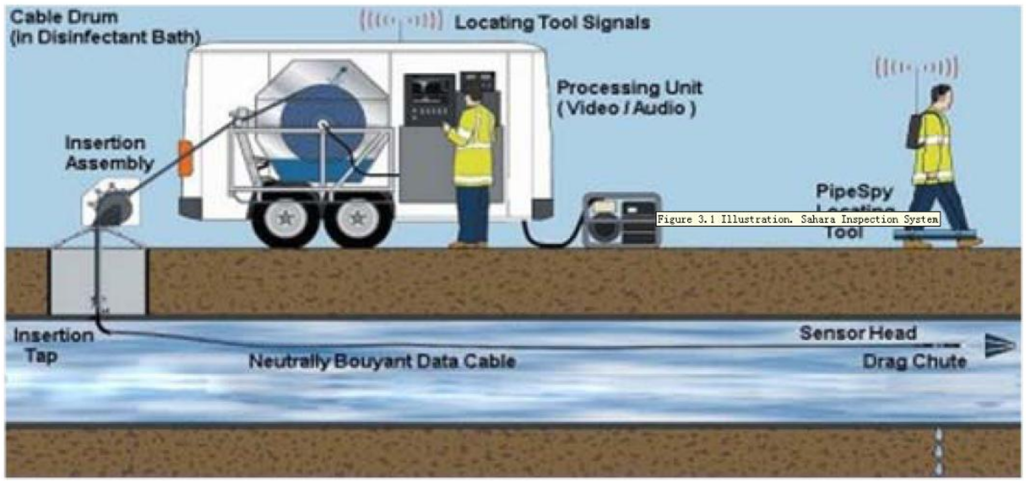
Challenges of pipe inspection: Turbulence, deployment, cost, power, Wireless Communication



Flow created by sinking current into Storm Sewer

- Deployment cost must be low, it is preferable to use existing tapping sites (2 – 6 inch) as insertion, extraction, and measurement sites.
- Low-cost → Miniaturization → Low-power and integration
- Wireless communication

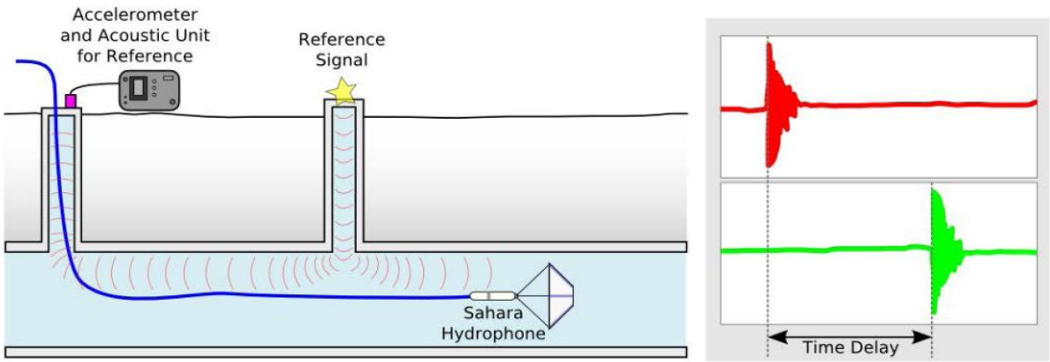
The Pressure Pipe Inspection Company (PPIC)



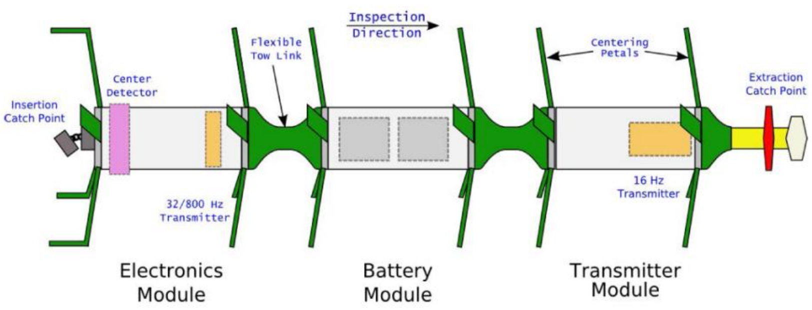
Sahara Inspection System

Video Head

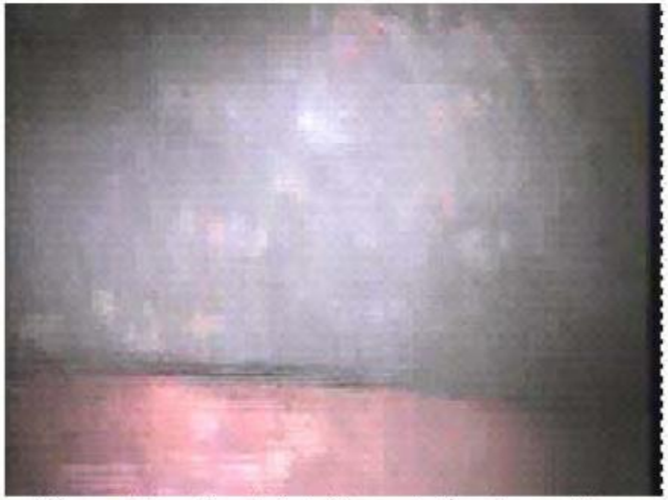
- Both acoustic and video measurement are available.
- CCTV provides the best in terms of accuracy



Wall thickness measurement



Video Samples from Sahara System



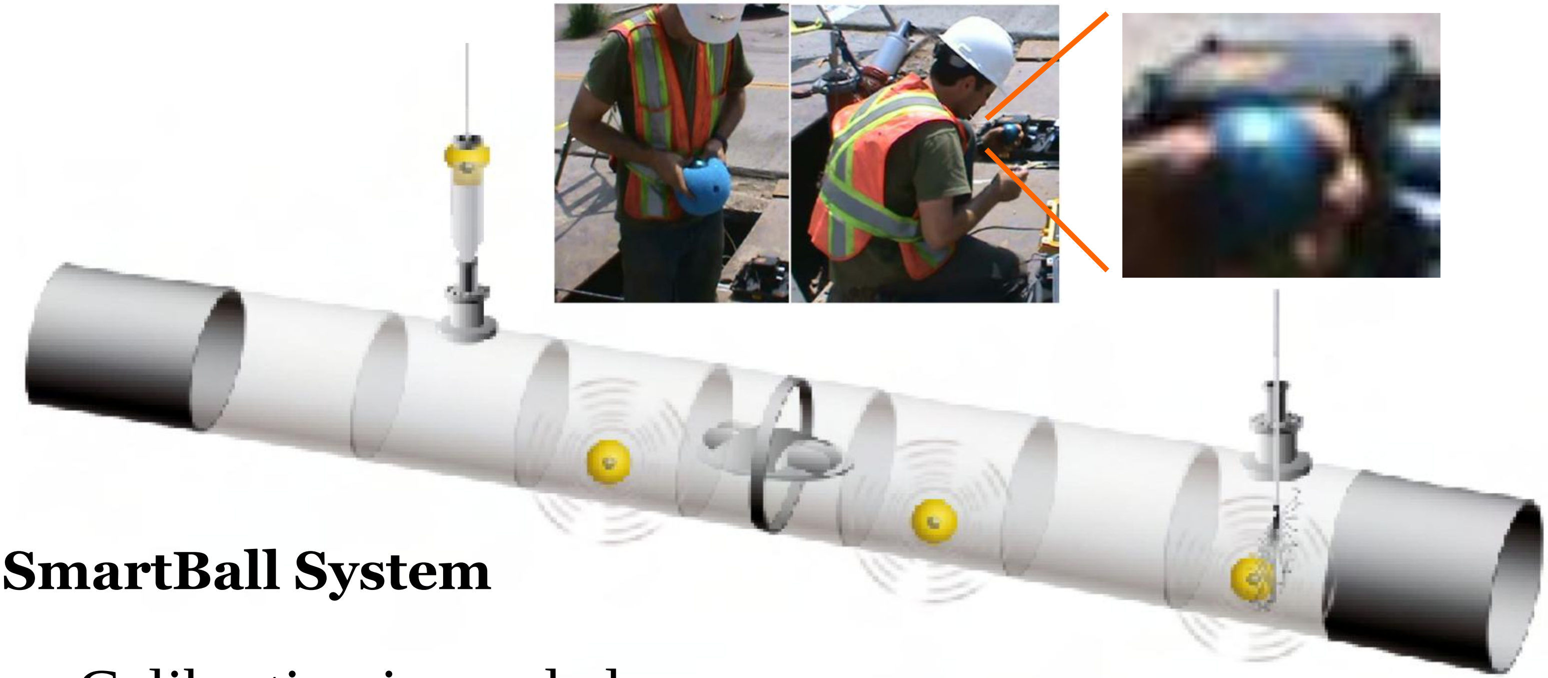
Close-Up of a Joint Gap at the Insertion

Example of an outlet

Extraction Point, 24x24x12" Tee

Example of Large Air Pocket

Pure Technologies Ltd.



SmartBall System

- Calibration is needed
- Data is not available for real-time diagnosis.
- The most expensive technology (USD$9/ft).
- Accuracy and range (limited by battery lifetime).
- Ball (1000-2000 US$) can be lost

Echologics Engineering Inc.

Wireless Transmitter **Hydrophone Installation**

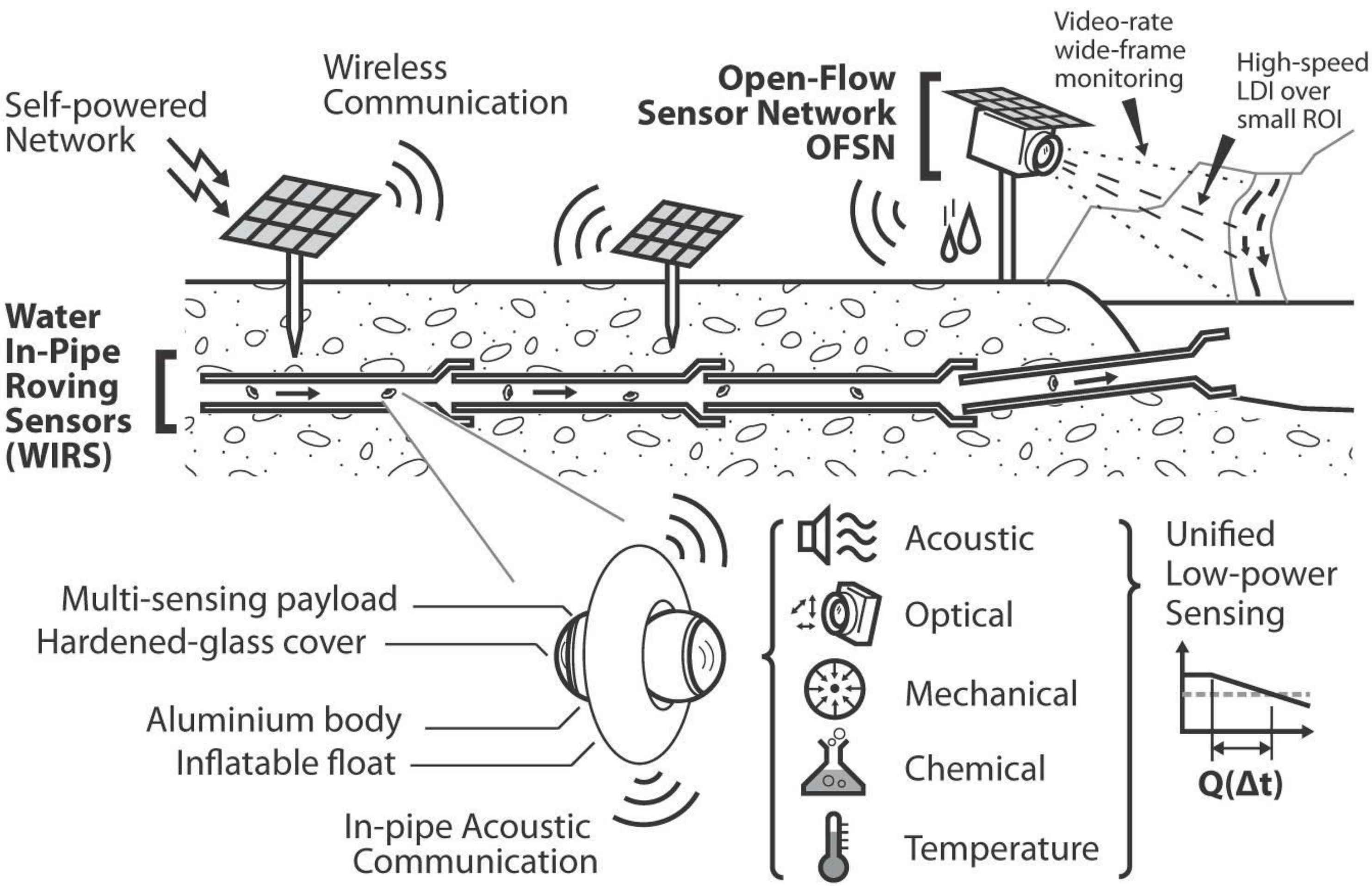
- Installed at the surface of the pipe (limitation).
- Poor sensitivity and limited dynamic range.
- Worst accuracy.
- Lowest in cost (USD $2/ft) and easiest to deploy.

Summary on the Sate-of-the-art

	PPIC Sahara	Pure Tech. SmartBall	Echologic
Pressure resolution (gpm)	0.06	0.06	0.6
Range (km)	2	25	-
Installation	Tethered	Swimming	External
Cost (USD$/ft)	2-4	4-9	2-3

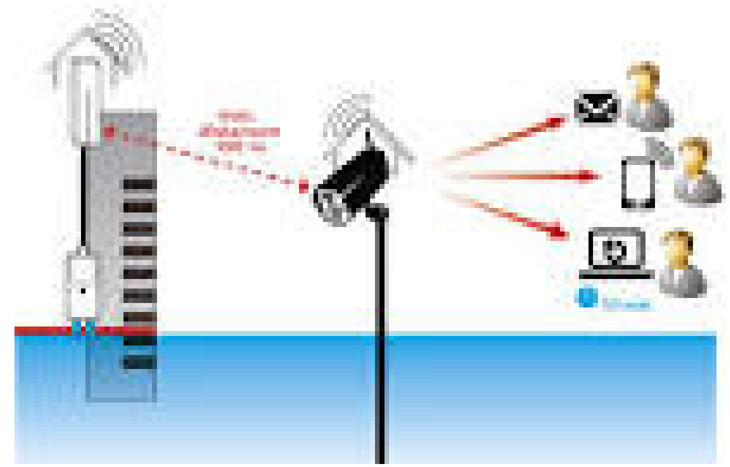
- Echologic system is the most cost efficient but present many issues: Accuracy, Deployment issues (surface of the pipe),
- Smart Ball offers very interesting features but “offline” approach, expensive
- Acoustic medium is prone to interference from: traffic, construction, and air pocket.

Objective: Multi-sensing platform



- Water In-Pipe Roving Sensors (WIRS) rove inside the pipe.
- Open-Flow Sensor Networks (OFSN) for monitoring open-flow areas.

Challenges for open flow video sensors



- Existing open flow sensors include Water Level Sensors and video camera
- Very expensive, costly maintenance and hence deployed at very small scale and only downstream (Urban areas).
- Need a separate energy harvesting unit (costly).
- Transmit only few frames/day

"Wireless Camera Network"
Can we deploy cameras at large scale?

Challenges:

- Vision sensors are power-hungry
- Transmit a lot of data (1.1Mpixel translates to 1GB/s)

Key questions:

- Can we use the light to self-power the sensor?
- Can we transmit information rather than data?

Objectives:

1. **Ultra-low power vision sensors**
2. **Self-powered sensors (Sensors that can be reconfigured as energy harvesters**
3. **Design intelligent data converters (Analog-to-information Converters rather than ADC).**

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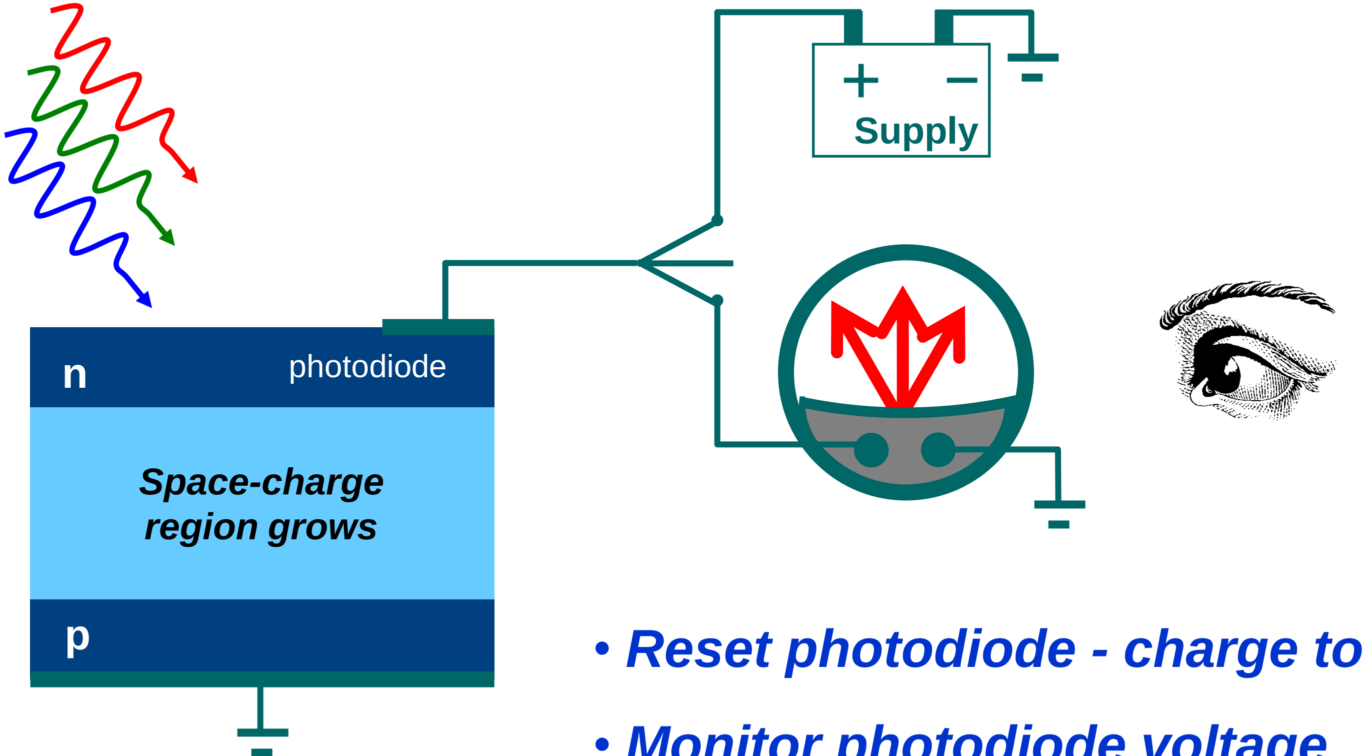
Conventional Image Sensor

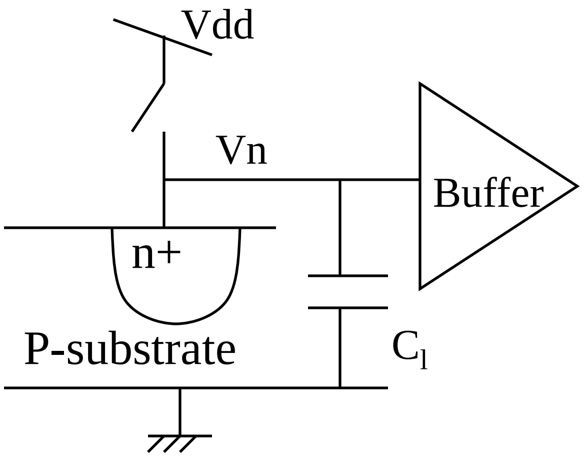


- *Reset photodiode - charge to V_{supply}*
- *Monitor photodiode voltage*
- *Photons discharge photodiode*
- *Measure final photodiode voltage*
- *Reset - repeat*

Conventional Image Sensor

- The three phases operation (basic of APS, by E. Fossum at JPL).

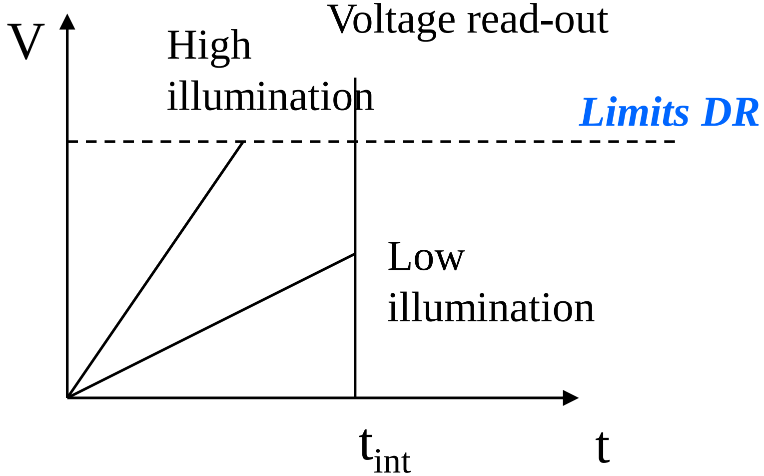
1. Reset: The switch is closed and the voltage Vn is reset to Vdd
2. Integration: The switch is open and charges are collected during t_{int}
3. Read-out: At the end of integration the accumulated charges or voltage is read-out.



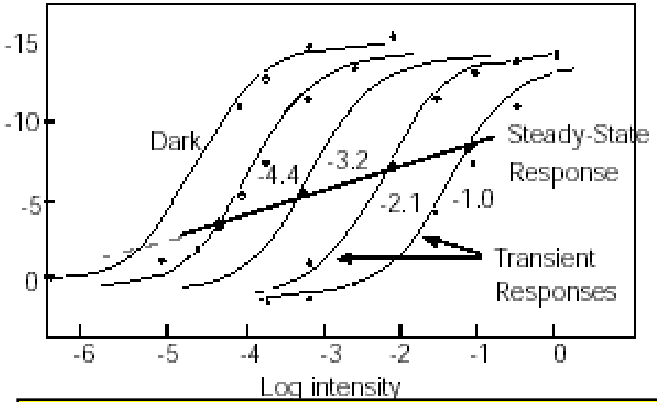
$$Q = (i_{ph} + i_{dc})t_{\text{int}}$$

$$v_n = v_{dd} - \frac{i_{ph} + i_{dc}}{C_l} t_{\text{int}}$$

Read-out a voltage
Fixed time



Can we learn from Biology?

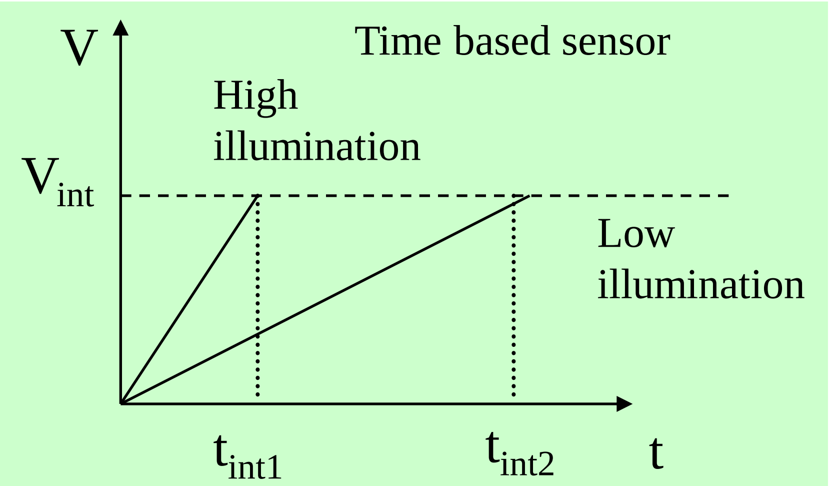


Gain adjustment mechanism in the turtle cones (T.Delb.)

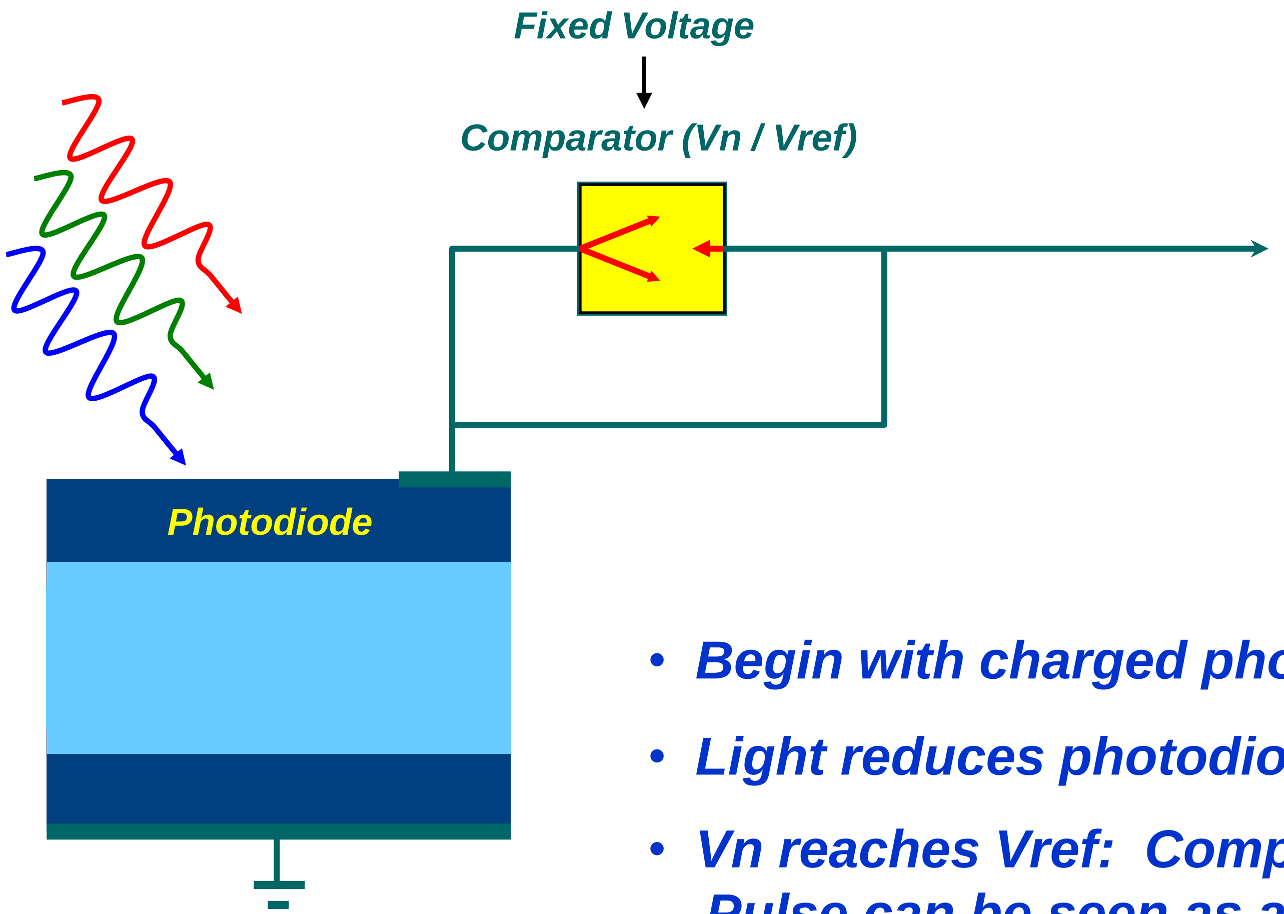
Biological Inspirations

Information is coded in the time domain (pulse train)

Alternative Solution
Fixed voltage

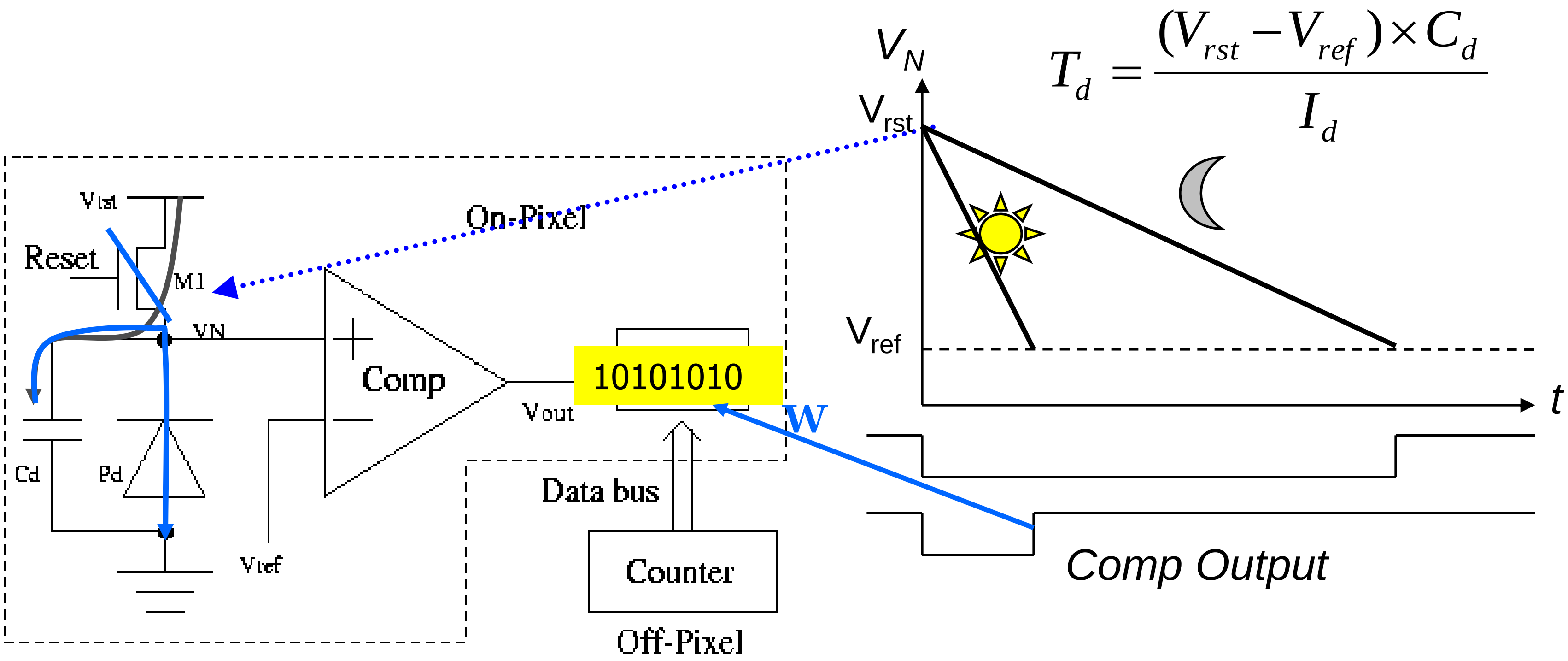


Time-Based Vision Sensor



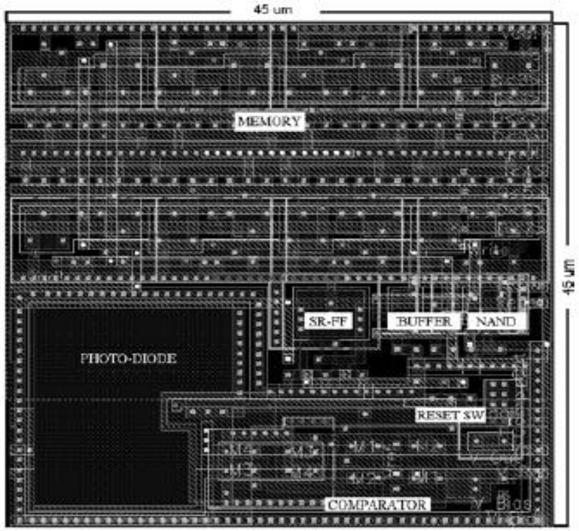
- *Begin with charged photodiode*
- *Light reduces photodiode charge*
- *Vn reaches Vref: Comparator triggers*
  Pulse can be seen as a time information
- *Feedback pulse restores charge*

PWM Sensor: Principle

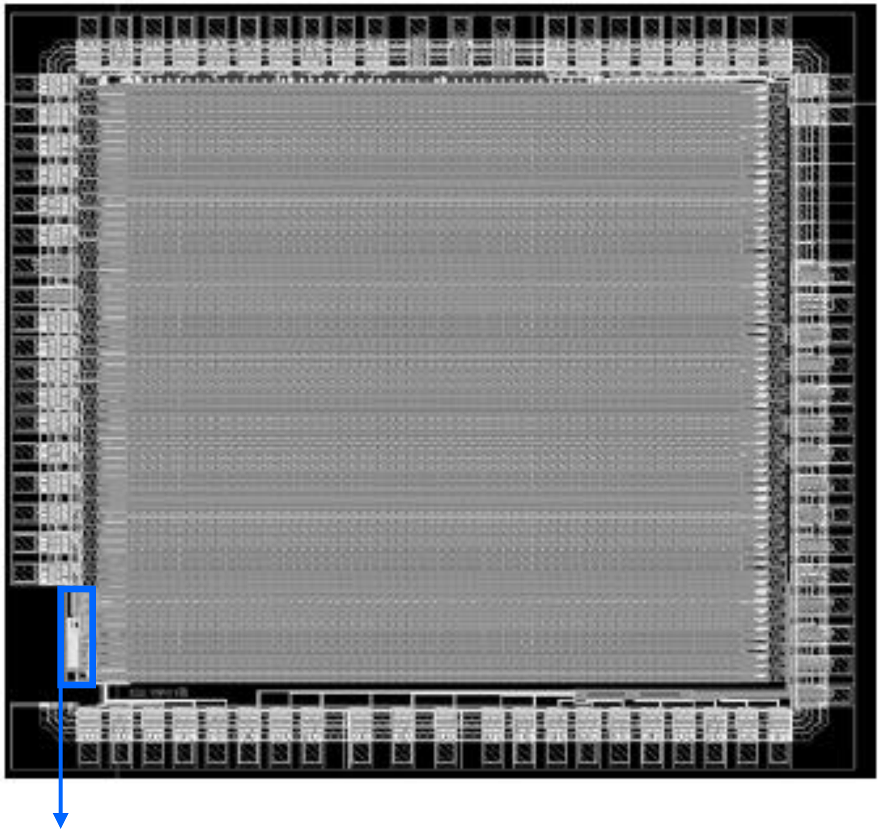


- The comparator pulse is used as a write pulse to the memory which will then write in from the global data bus
- The comparator pulse is also used to reset the voltage of the photodiode to Vdd → Feedback circuit.

Prototype Chip



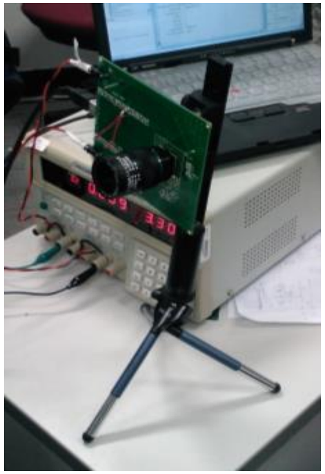
Feature	Specifications
Resolution	64 x 64
Pixel size	45 x 45 υm^2
Fill-factor	12%
Image array area	95% of the chip area
Die size	15 mm^2
Dynamic range	100 dB
Process	0.35 um CMOS tech

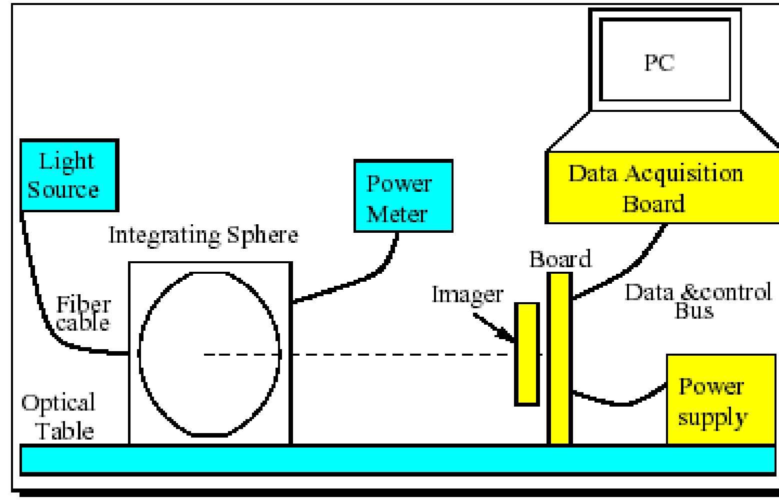


Control circuitry:

* NUQ circuit
* Blanking circuit

Sample Images and results





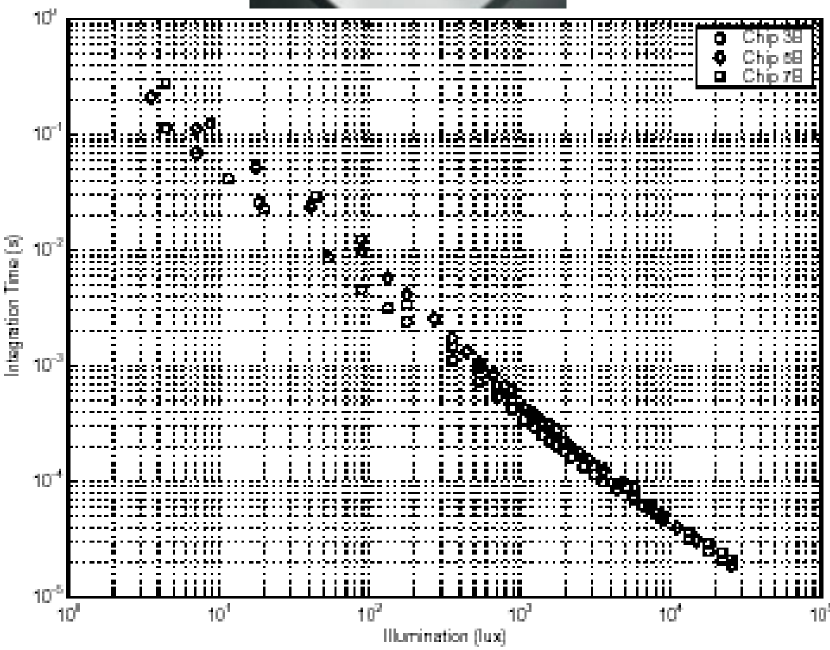
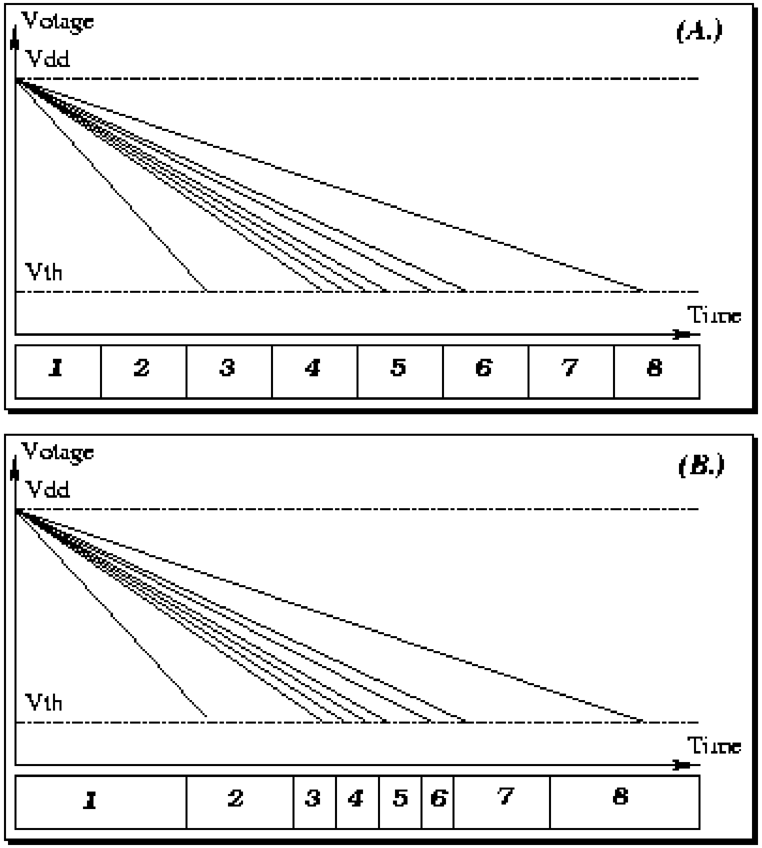
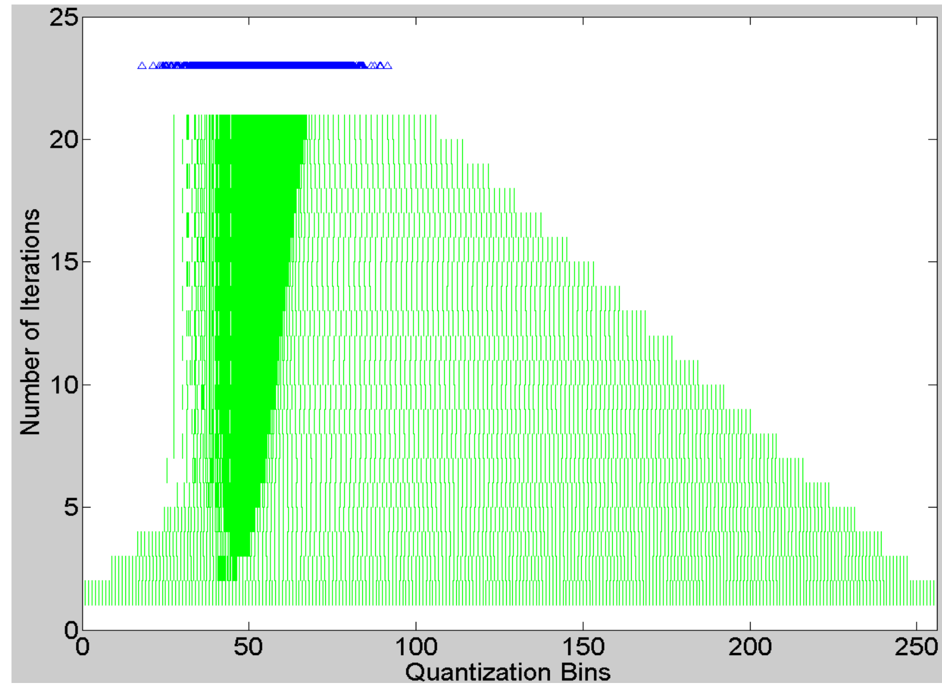


Image Processing Perspective
Adaptive Quantization



$$\Delta x_j = \eta\left(\sum_{k=j+1}^{N}\delta_k^r \frac{\|_{Rk}}{N-j} - \sum_{k=1}^{j}\delta_k^r \frac{\|_{Rk}}{j}\right) j = 1,\ldots,N-1$$



- Quantization boundaries are adjusted as the pixels' spikes are received.
- The quantization levels are adapted to the image statistics

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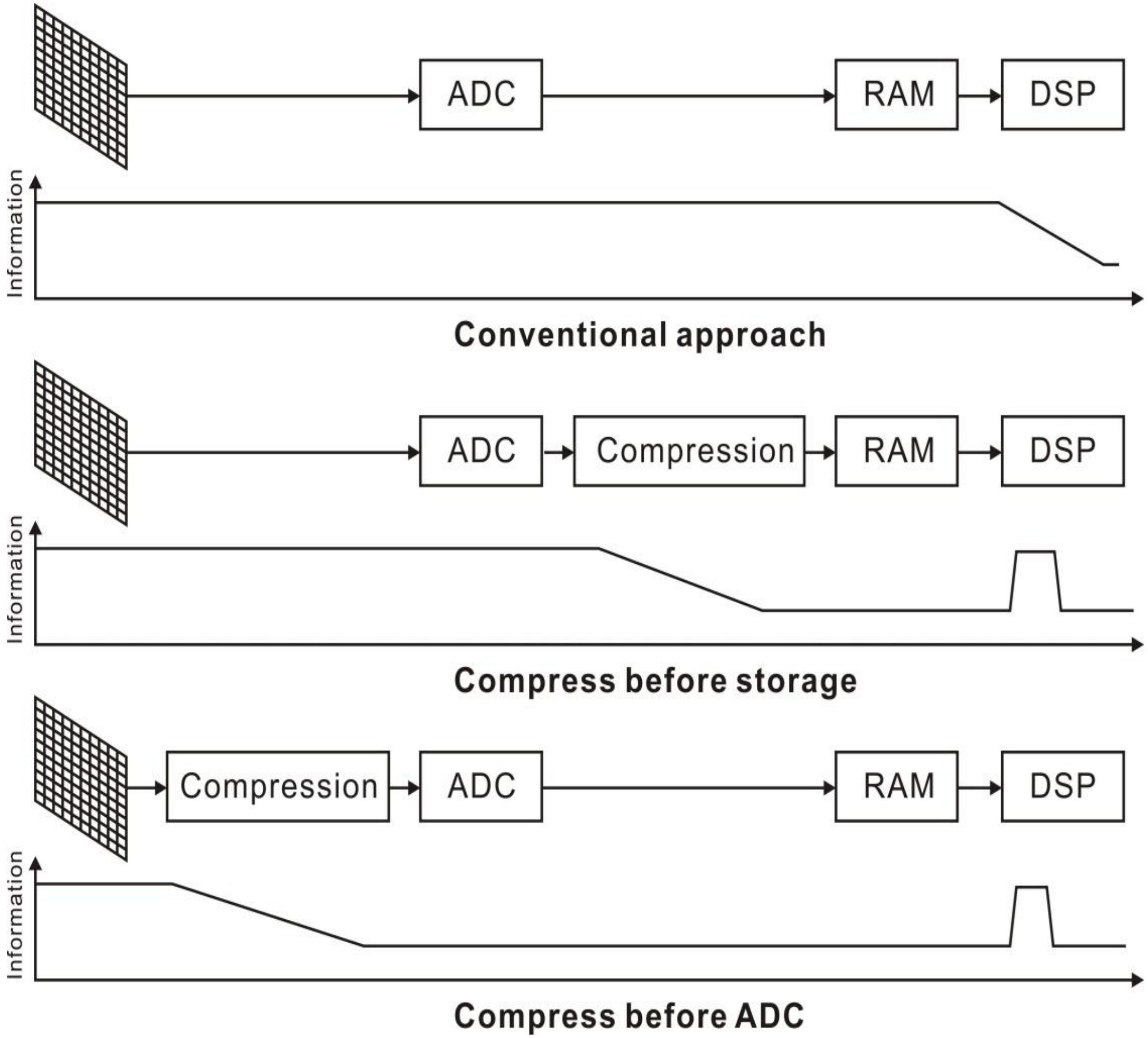
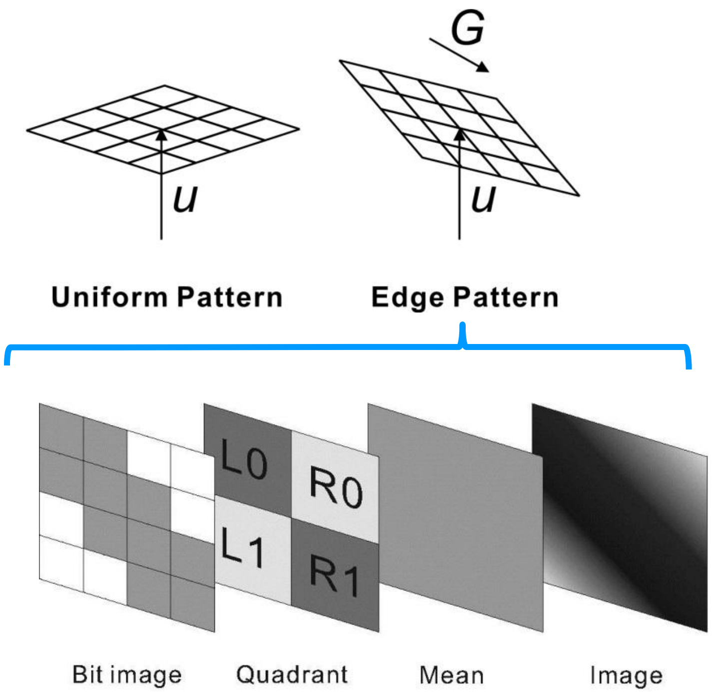
Analog to Information Imager



- Key idea: Compression is performed prior to ADC
- Analog read-out attempts to remove redundancy.
- Image is divided into blocks
- Useful information within the block is extracted in analog domain.
- ADC only operates on useful data

Analog to Information Imager



$$u(4k, 4l) = \frac{1}{4} \times (L1 + L0 + R1 + R0)$$

$$G(4k, 4l) = \frac{1}{4} \times (|L0 - R1| + |L1 - R0|)$$

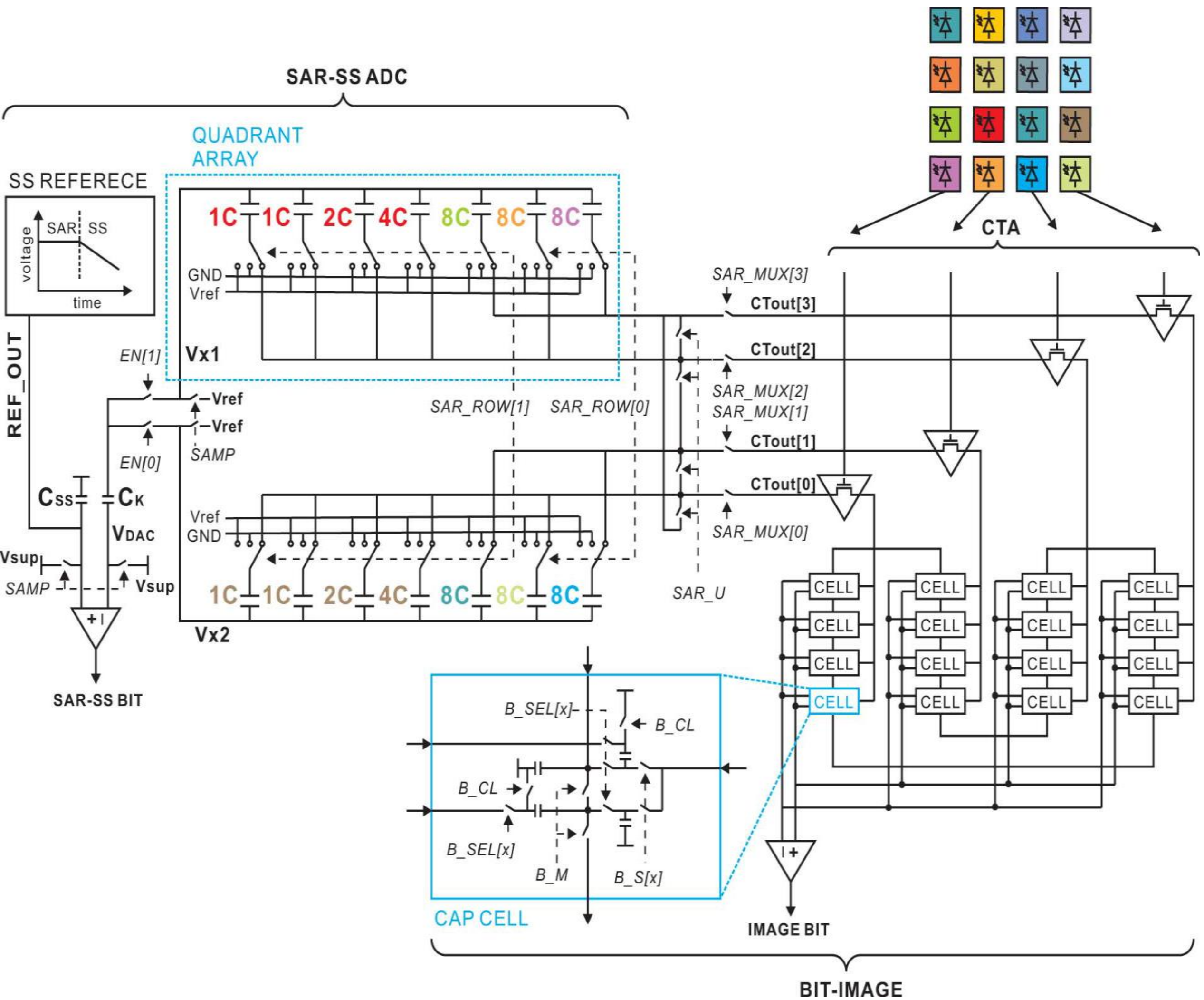
" A 12 pJ/pixel Analog-to-Information Converter based 816 x 640 CMOS Image Sensor," IEEE Journal of Solid-State Circuits, submitted 2013.

- If the gradient is within a threshold: uniform pattern (UP), only the u is sent
- Otherwise it's an edge pattern (EP) and the mean, G, and the bit-mage are sent
- Analog switch cap techniques are used to compute u, G and ADC is ON only when needed (EP) (10% of the time).


Original Image


Compressed
31.2 dB PSNR @ 0.7 bpp

Analog to Information Architecture



- A single quadrant is processed in one read-out cycle
- Switched Cap techniques are used to compute the mean and quadrants
- SAR-SS is used for best trade-off between power and area.
- ADC is On only for Edge Block → power saving

Prototype Measurement

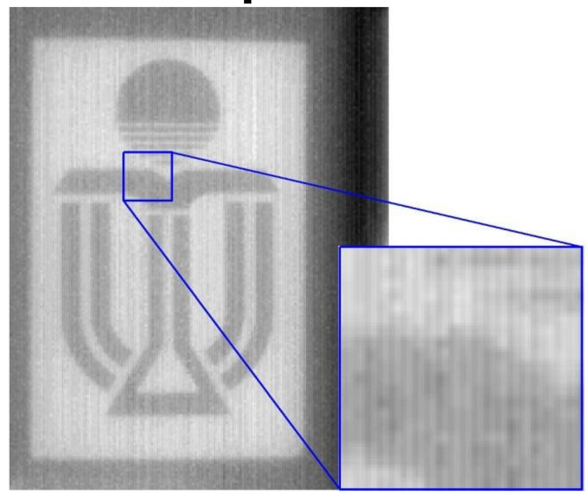
	Compressed	Raw
Process	0.18 μm 1P6M Mixed-signal CMOS	
Supply voltage	3.3 V, 1.8 V	
Chip clock	4 Mhz	
Imager size	816 $\times$ 640	
Frame rate	111 fps	28.7 fps
Pixel size	1.85 μm $\times$ 1.85 μm	
Fill factor	13 %	
Dark current	<4307 e^-/sec	
Saturation level	7718 e^-	
Conv. gain	35.76 $\mu V/e^-$	
Sensitivity	309 e^-/Lux.sec @ 1167 Lux	
Dynamic range	46 dB	34 dB
ADC resolution	8b	9b
Temporal noise	2 LSB_{rms}	4 LSB_{rms}
Power	0.69 mW	0.72 mW
Energy	12 pJ/pixel	48 pJ/pixel
Data rate	3 bpp (1 bpp after FPGA)	9 bpp
PSNR	20 dB	25 dB

We can achieve 0.7BPP and 30dB SNR

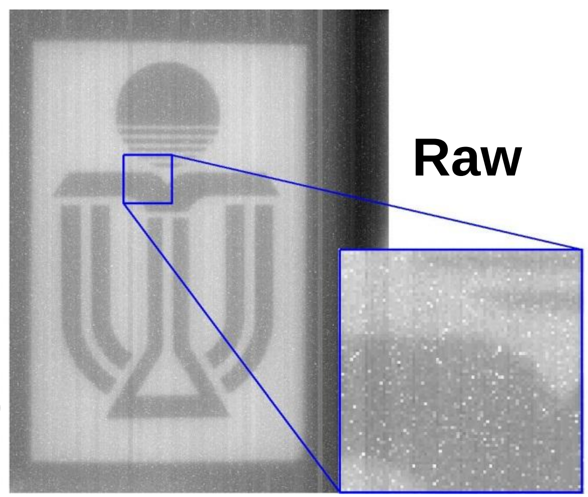
Power level of less than 1mW (12pJ/p) (lowest ever reported power for imager)

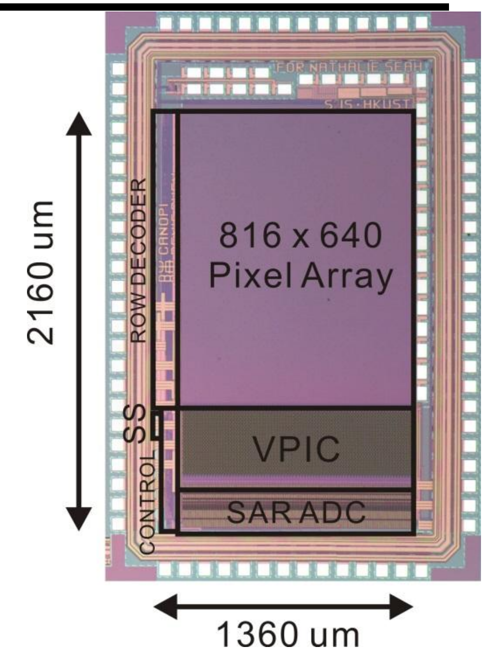
We can achieve about 111fps

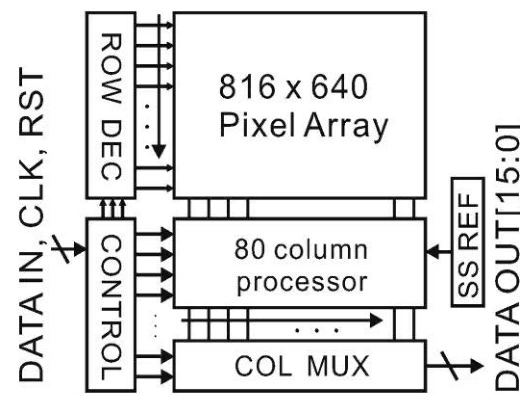
Compressed



Raw







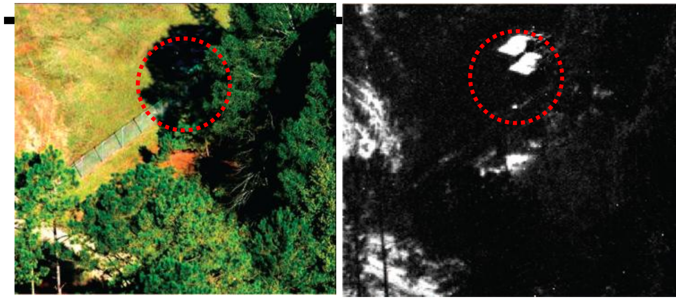
" A 12 pJ/pixel Analog-to-Information Converter based 816 x 640 CMOS Image Sensor," IEEE Journal of Solid-State Circuits, May 2014.

Comparison

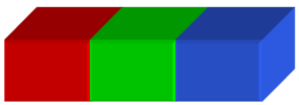
Reference	[19]		[25]	[26]		[10]	[17]		[16]		This work	
Year	2012		2007	2009		2011	2008		2006		2013	
Algorithm	CS		Lossless	Haar wavelet		QTD	SPIHT		DCT		VPIC	
Architecture	Column level		Column level	Column level		Chip level	Pixel level		Pixel level		Column level	
ADC	$\Delta\Sigma$		Single slope	$\Delta\Sigma$		Single slope	none		none		SAR	
ADC resolution	**12b**		8b	8b		8b	-		-		9b	
Technology (μm)	**0.15**		0.35	0.35		0.35	0.5		0.5		0.18	
Supply (V)	3.3, 2.0, 1.8		3.3	3.3		3.3	-		3.3		3.3, 1.8, 1.2	
Area (mm^2)	2.9×3.5		2.6×6.0	4.4×2.9		3.3×3.2	2.3×2.3		2.4×1.8		2.16×1.36	
Resolution	256×256		80×44	128×128		64×64	33×25		104×128		**816 × 640**	
Pixel pitch (μm)	5.5		32	15.4		39	69		13.5		**1.85**	
Fill factor (%)	-		18	28		12	21		46		13	
Pixel circuit	4T pinned PD		8T	7T		PWM DPS	Hetrerogenous		Floating gate		3T APS	
DR (dB)	78		-	-		>100	-		-		34	46
Frame rate (fps)	120	1920	435	30		-	**10000**		25		28.7	111
Throughput (Mp/s)	7.9	125.8	1.5	0.5		-	8.3		0.3		15.0	58.0
Power (mW)	93.1	96.2	150	26.2		17	**0.25 @ 30fps**		2		0.72	0.69
Energy (pJ/pixel)	11838	765	21973	53304		-	10101		6010		**48**	**12**
Compression ratio	1	16	<1.5	3.5	8	9.1	**80**	8	1.3	13.7	1	8
PSNR (dB)	-	32.5	-	32	15	23	24.5	40	**47.1**	25.7	25	20

- Lowest energy/power consumption ever reported due to AIC and novel circuit techniques (dynamic circuits).

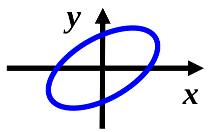
Polarization Imaging

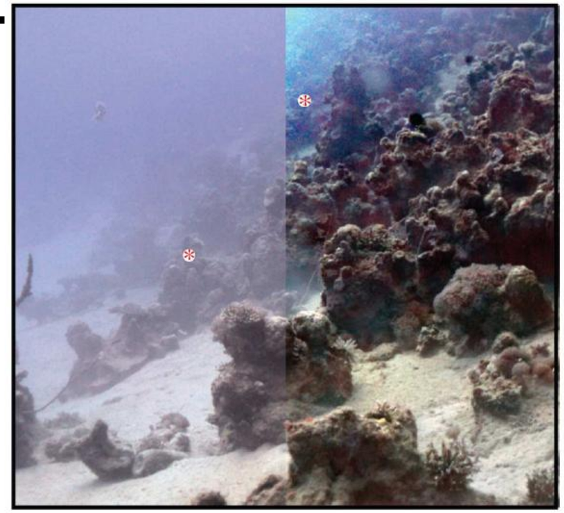


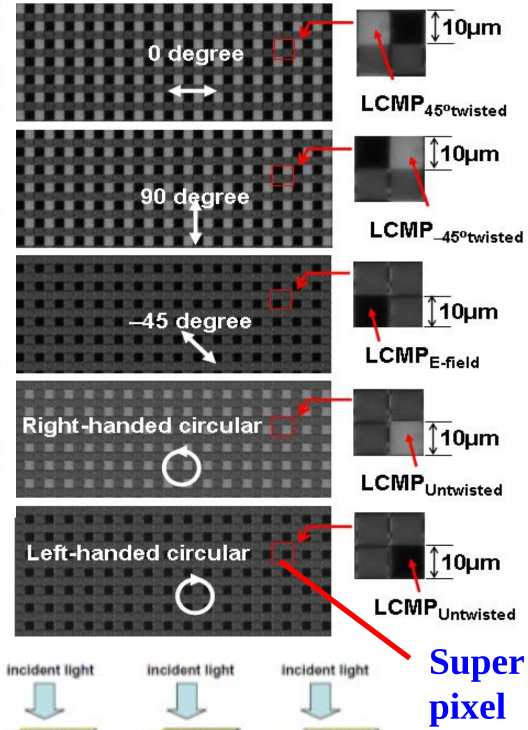
Colour

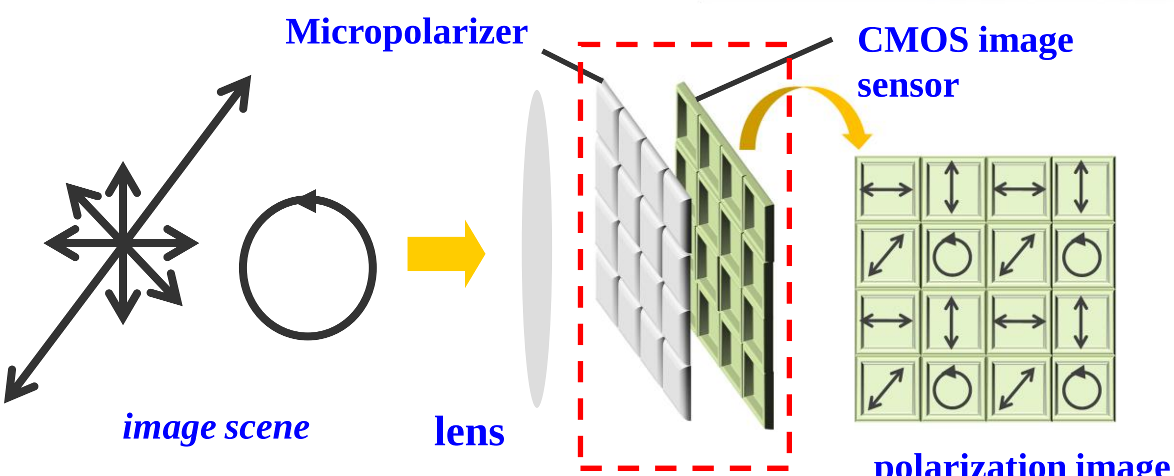


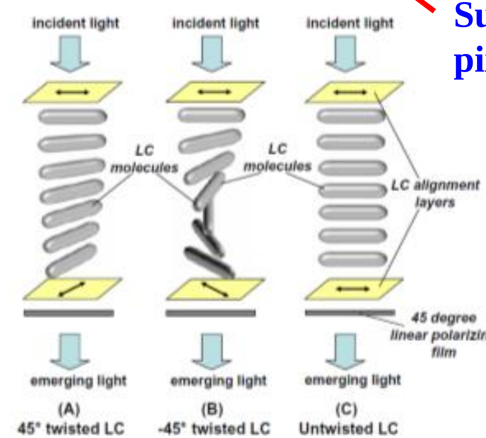
Polarization











Fully integrated real-time CMOS polarization image sensor

"Liquid-crystal micro-polarimeter array for full Stokes polarization imaging in visible spectrum", Optics Express, 2010.

"Photo-Aligned Liquid-Crystal Micro-polarimeter Array and Its Manufacturing Method," *US Patent 12/784,355*

Talk Agenda –Towards Autonomous sensors

- State-of-the-Art Water Sensing
- Time-Domain Imaging –Low power alternative
- Time-Domain Image Processing – Smart Vision Sensor
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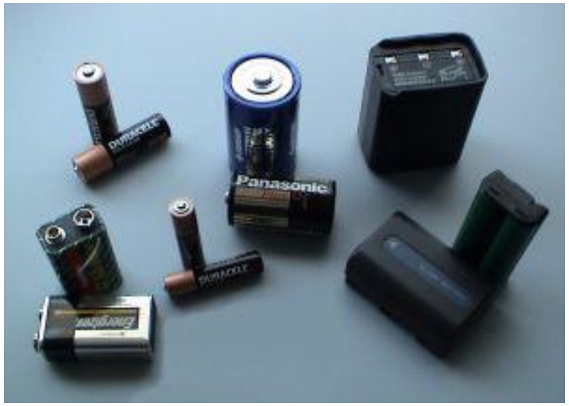
- Energy harvesting Image Sensors
- Conclusion

Power is still the main issue

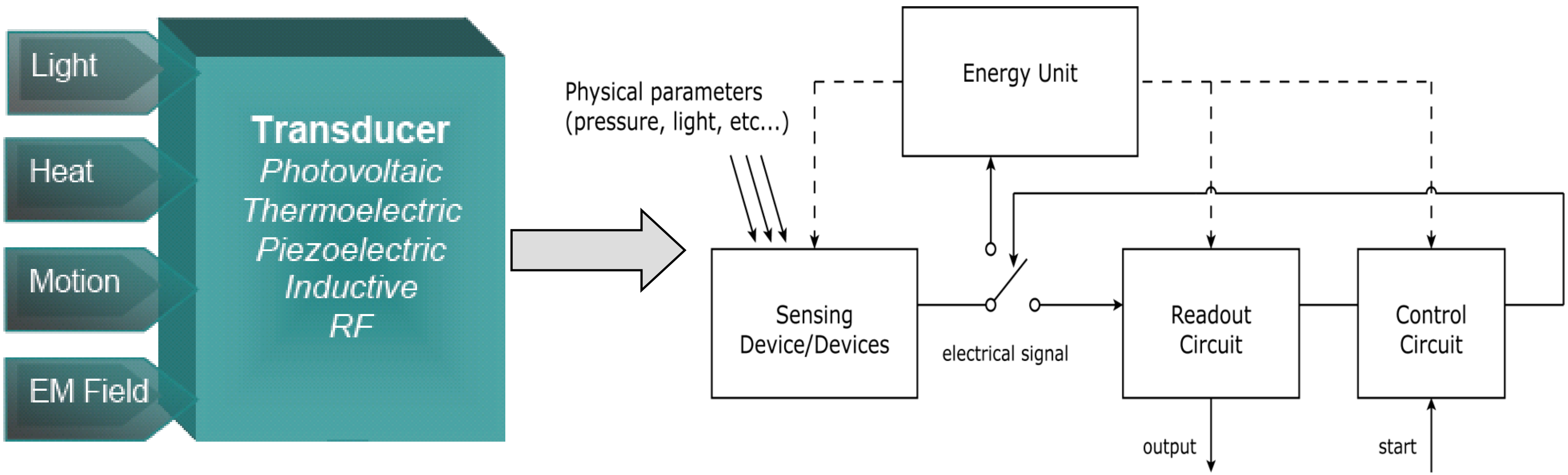


- Portable system and wireless sensing platforms lifetime is usually limited battery capacity
- Considerations for cost and system lifetime
  - Low power/energy consumption
  - Passively powered/energy harvesting capability

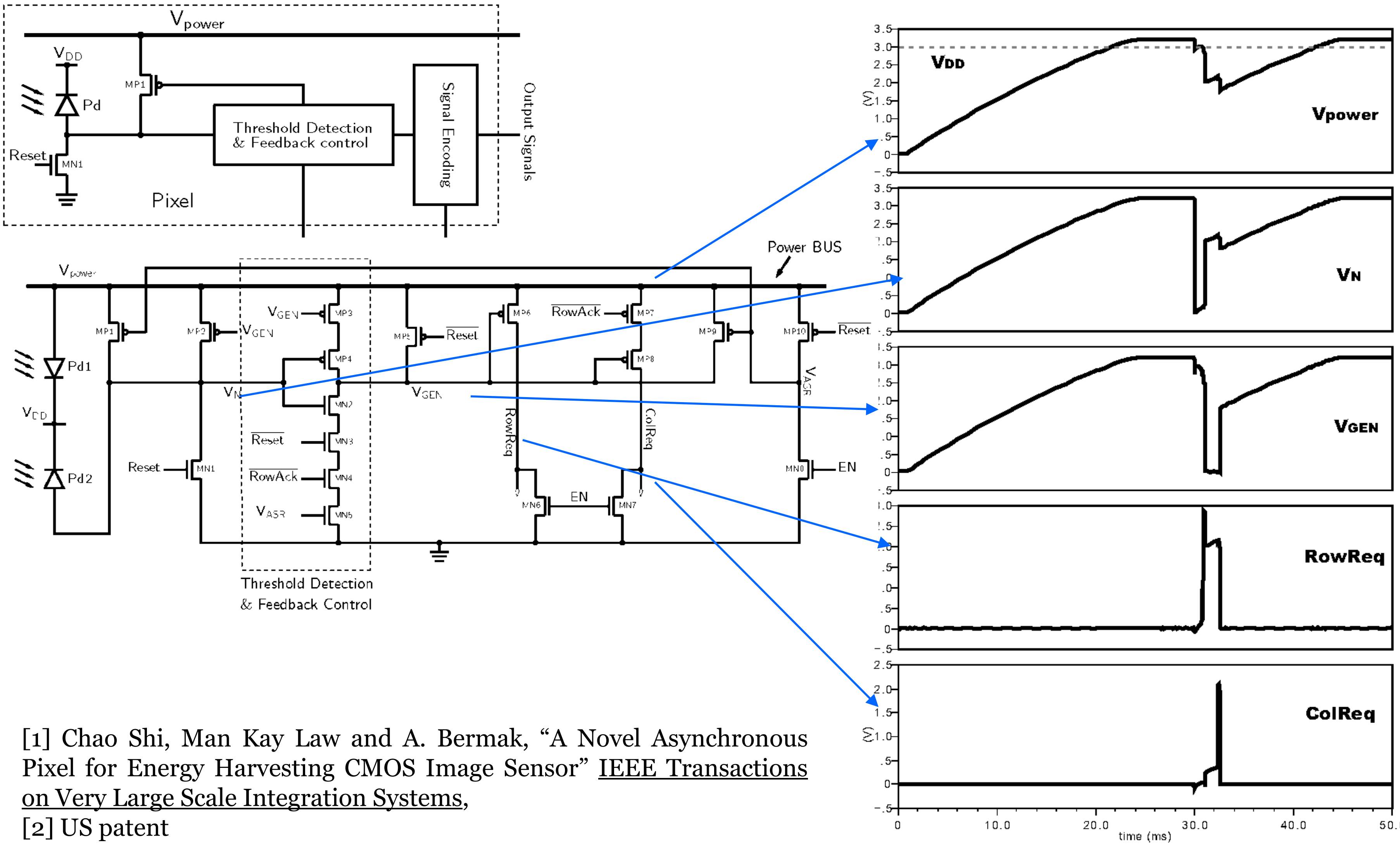
Asynchronous Sensors –Energy harvesting

Using the same photodetector for Sensing/Energy harvesting: Improved FF and pixel size

=> Key Idea – Time domain imaging



Proposed concept

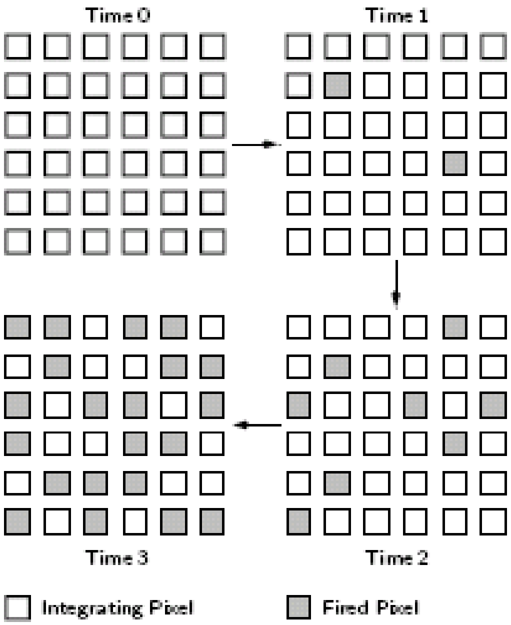


[1] Chao Shi, Man Kay Law and A. Bermak, "A Novel Asynchronous Pixel for Energy Harvesting CMOS Image Sensor" IEEE Transactions on Very Large Scale Integration Systems,

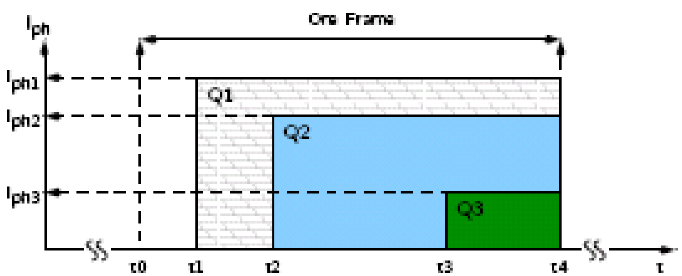
[2] US patent

Smart Sensory Integrated Systems Lab

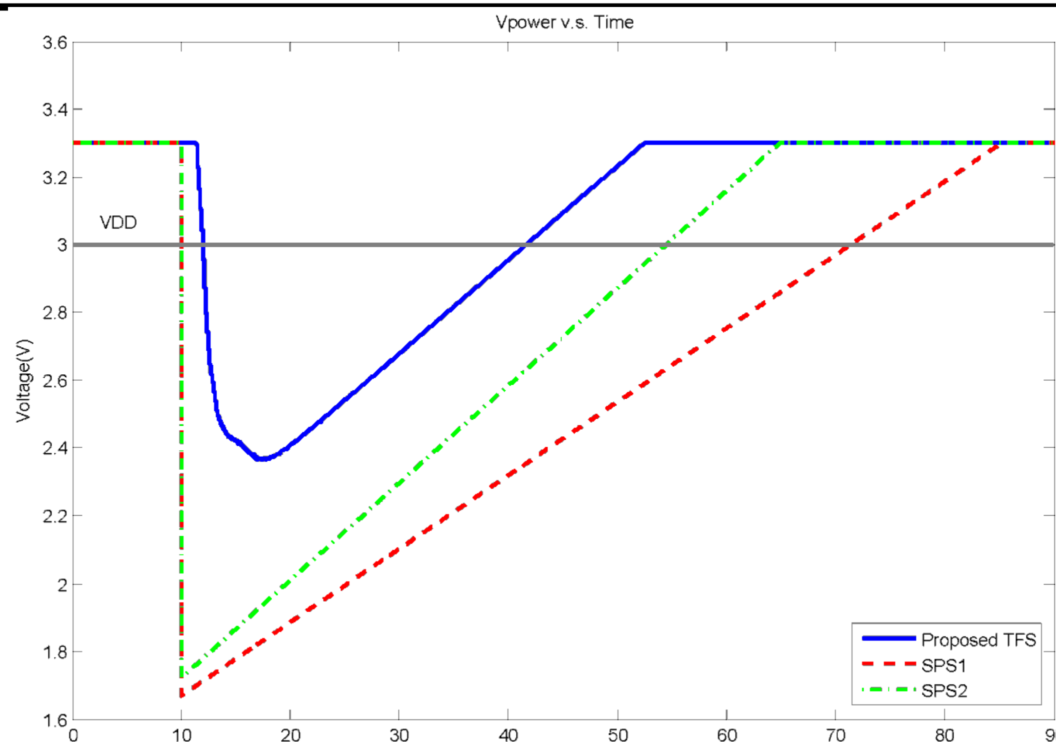
Avalanche Energy generation

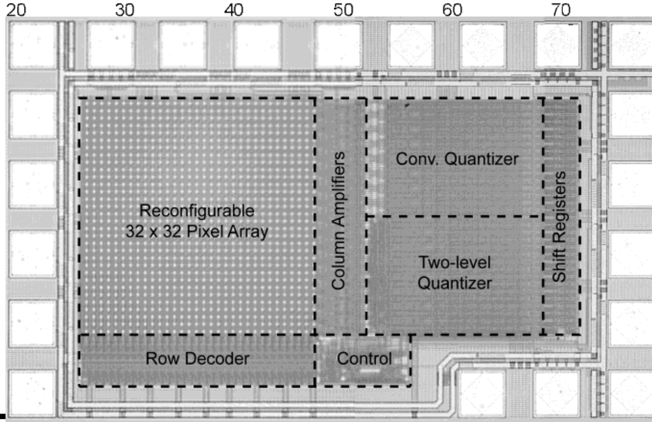


(A)



(B)

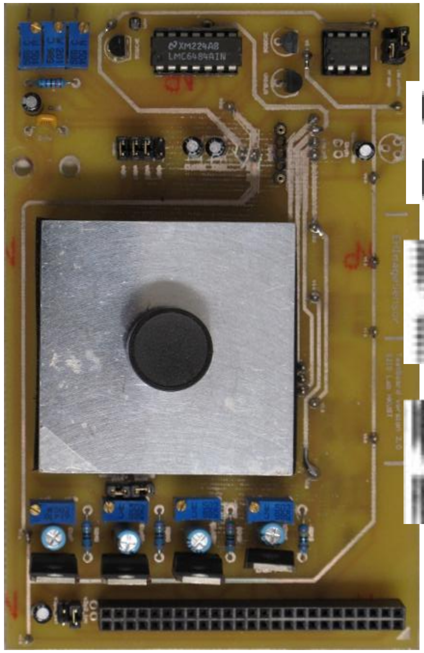




Reconfigurable array: Performance summary

	[24]	[25]	This work
Process	$0.35\mu m$	$0.35\mu m$	$0.35\mu m$
Array Size	160×240	128×96	32×32
Supply Voltage	3.3V/1.5V	1.35V	1.5V
Pixel Size	$5.6\times5.6\mu m$	$10\mu m^2$	$15\times15\mu m$
Fill Factor	32%	18.5%	21%
Frame Rate	N/A	9.6fps	up to $21fps$
Dynamic Range	68dB	53.7dB	>84.9dB
FPN	0.52%	0.12%	18.42%
Power Consumption	$3.12mW^{(2,5)}$	$0.42\mu W^{(1)}$ $55.2\mu W^{(2)}$	$15.8\mu W^{(2,3)}$ $8.83\mu W^{(2,4)}$
Normalized Power (pW/frame/pixel)	N/A	$3.6^{(1)}$ $468^{(2)}$	$735^{(2,3)}$ $821^{(2,4)}$
Power Generation (nW)	No	No	35.6 @ 29kLux, 4.7MΩ load

(1) Array only (2) Whole chip (3) Full res. (4) Half res. (5) Estimated



- Incorporate sensing and harvesting capabilities is feasible
- Power generated vs. power consumed: duty cycle of about 1%

[24] D. Lee et al, "Low-Noise In-Pixel Comparing Active Pixel Sensor Using Column-Level Single-Slope ADC", IEEE Trans. Electronic Devices, vol. 55, no. 12, pp. 3383-3388, Dec. 2008.

[25] K. Kagawa et al, "A 3.6pW/frame pixel 1.35V PWM CMOS Imager with Dynamic Pixel Readout and no Static Bias Current", IEEE Int. Solid-State Circuits Conf. Dig., pp. 54-55, Feb. 2008.

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Conclusion

- Smart water system is a multi-disciplinary area: Requires collaboration from different disciplines.
- Electronic Engineers have a key role to play particularly: Sensors design and communications
- Smart Water Systems need to be equipped with sensing, processing and wireless comm and need to be low power/harvest energy.
- Time-domain encoding (in analogy with biological systems) presents a number of advantages:
  - Immunity against noise: as data are represented in digital domain.
  - Reduced power: as data can be represented in single transition.
  - Simplified processing
- "The difficulties posed by integrating: sensing, processing and Communications for smart water system applications will eventually lead to more opportunities for innovations"

Acknowledgments

- My students who have significantly contributed to this work
- HK RGC for providing funding for this research program.