Indirect X-ray Pixel with High Dynamic Range by using combined counting & integration

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Outline

• Purpose
• Background: photon counting X-ray
• Proposed pixel topology
• Circuit concept and layout
• Initial results
• Conclusion
Chapter 1

PURPOSE
Purpose

• Illustrate the concept, design and initial measurements of a Pixel for indirect X-ray detection
• Providing combined photon counting and charge integration capability
Purpose

- We demonstrate the huge dynamic range achievable of 100,000:1 (100dB)
  - At low flux: quantum limited photon counting
  - At high flux: saturation only limited by the size of the integrating capacitor
Chapter 2

BACKGROUND: PHOTON COUNTING X-RAY
Background

- Caeleste ISSCC 2011:
  First demonstration of indirect X-ray photon counting
**Background**

- **X-ray photon counting pixel with two or more energy bands** (*IISW 2013*)

![Diagram of X-ray photon counting pixel](image)

- Light flash
- Photo diode with scintillator
- Charge packet
- Sense amplifier (band filter + preamp)
- Comparators
- Analog Voltage pulse train
- Binary pulse train
- Reference 1
- Reference 2
- Counter 1
- Counter 2
- MUX
- To detector output
Background: *limitations*

- **Count range**
  - Limited by size (Silicon area, FF, QE…)
  - Limited by counter type
- **Power consumption**
  - Count rate, counter paralysis
  - Number of energy channels (“colors”)
- **Circuit noise**
  - Difficult to detect low energy photons
  - All photons below threshold are not detectable
  - False positives / false negatives
Overcoming the limitations?

- **Count range**
  - Limited by size
  - Limited by counter type

- **Power consumption**
  - Count rate, counter paralysis
  - Number of energy channels

- **Circuit noise**
  - Difficult to detect low energy photons
  - Lost low-energy photons
  - False positives / negatives
Chapter 3

PIXEL TOPOLOGY
Combined photon counting & charge integration

Pixel topology

Charge packet
Sense amplifier
Pulse shaper
Comparator
Binary pulse train
Analog Voltage pulse train
Binary pulse train

Integrator reset

Light flash
Photo diode with scintillator

Analog counter staircase & Integrator ramp
Electrons

To imager output

multiplexor
Pixel topology

Combined photon counting & charge integration

- The photo-charge packet
  - Triggers the pulse shaper
  - Simultaneously integrated on a capacitor
- All photocurrent is integrated
  - No photon loss
  - Both counted and not counted
- Intrinsic color X-ray
  - Weight of counted photon: 1
  - Weight of integrated photon: $\propto h\nu$
Chapter 4

CIRCUIT DESIGN & LAYOUT
Evolution of concept

Counting only

Counting & Integration

Indirect X-ray counting & integrating pixel with HDR

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Evolution of concept

- Mode of operation: Counting & Integration
Evolution of concept

- **Mode of operation:** Counting & Integration

Diagram:
- Pulse output to comparator
- ~DC
- Drain
- Gate
- V
- Integrator output
- V
- Pulse output to comparator
Test pixel layout
Chapter 5

INITIAL RESULTS FROM THE PROTOTYPE
Prototype device

- Single pixel
- XFAB XS018 technology
- Single pinned photodiode 20*100µm
- Pulse shaper with combined integrator
- Analog readout of integrator
- Binary readout of comparator  
  (pulse, SR FF or Toggle FF)
- Integration capacitor: 1pF
- Minimum charge packet: ~ 350e⁻

All measurements performed using a LED
Response to large LED pulses

Analog integration output

Binary comparator output
Combined Dynamic Range

Indirect X-ray counting & integrating pixel with HDR

Counts

Counts

Voltage (V)

Dynamic Range

Paralysis

Saturation

Read noise

Full well
Possible application domains

- Fluoroscopy
- Color X-ray
- High SNR imaging

Electronic read noise
X-photon shot noise
Counter saturation
Capacitor full well

N[^\gamma_{RMS}] vs. S[^\gamma]

1/\gamma \rightarrow 10/\gamma \rightarrow 100/\gamma \rightarrow 1000.../\gamma
Chapter 6

CONCLUSIONS
**Conclusions**

- **Combination of integration and counting proven**
  - Silicon proven with single pixel & LED
  - Exceptionally large dynamic range (~100dB)
  - Not shown: color X-ray capability

- **Future work**
  - Scintillator & X-ray testing
  - Application in large array
Thank you for your attention
Indirect X-ray counting & integrating pixel with HDR

References


- Bart Dierickx, Stijn Vandewiele, Benoît Dupont, Arnaud Defernez, Nick Witvrouw, Dirk Uwaerts, “Scintillator based color X-ray photon counting imager”, IISW, Utah, June 2013


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