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Desigr<br>CMOS<br>time Sand<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester<br>Caelester Calest<br>Explored units<br>Explored units of **PSC**<br>ent of a<br>second Prese<br>PIXE<br>Nove<br>**Callarge**<br>**Callec**<br>**Callec**<br>**Callec**<br>**Callec** Franceschilder<br>
School School<br>
School<br>
Carried Design and measurement of a large CMOS pixel with nanosecond collection time

S. Boulanger, A. Kumar Kalgi, J. De Vroe, N. Van Opstal, S. Regev (Etesian), B. **Dierickx** 

# Application

- Target?
	- o **Particle counting**
		- High repetition rate possible (avoid non-detection of subsequent events)
		- Should also work at low flux  $(< 10e^-/ns)$  of **incident electrons** (IE)
		- Low noise / high SNR, with underlying purpose:
			- ←Low False Positive (FP) rate
			- $\leftarrow$  Low False Negative (FN) rate
- oid non-detection<br>
.0*e<sup>-</sup>/ns*) of **incide**<br>
rlying purpose:<br>
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divided in parallel<br>
letection)<br>
P) on of subsequent<br>
cident electrons (<br>
:<br>
llel operating "pixe<br>
node APD) • Large total area of detector, subdivided in parallel operating "pixels"
	- **E counting**<br>
	In repetition rate p<br>
	buld also work at lext<br>
	Low False Positiv<br>
	Low False Negatinge total area of de<br>
	v energy ( $ke^-$ ) of l<br>
	e multiple options:<br>
	 intrinsic n diod<br>
	(Single-Photon Av<br>
	ators + visible ligh • Low energy  $(ke^-)$  of IEs
- Target?<br>
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 High re<br>
 Should<br>
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 We explore m<br>
 We explore m<br>
 PIN (p ir<br>
 APD (Aval<br>
 SPAD (Sir<br>
 SPAD (Sir<br>
 SPAD (Sir • We explore multiple options:
	- $\circ$  PIN (p intrinsic n diodes, direct detection)
	- o APD (Avalanche Photodiodes, LGAP)
- e possible (avoid lat low flux (< 10e<br>SNR, with underlyi<br>SNR, with underlyi<br>sitive (FP) rate<br>f detector, subdivie<br>of IEs<br>pns:<br>diodes, direct dete<br>todiodes, LGAP)<br>Avalanche Diode<br>ight sensing. o SPAD (Single-Photon Avalanche Diodes, Geiger mode APD)
	- $\circ$  Scintillators + visible light sensing.



# PIN diode for particle counting

### The straightforward solution: PIN

- $\circ$  For  $\sim$   $ke^-$ , Backside illumination is required
- The straightforwa<br>
o For  $\sim ke^-$ ,<br>
o One IE wil<br>
hole pairs<br>
o CSDA: Cc<br>
o There are<br>
  $\tau_{tr}$ , the<br>  $I_{photo}(ja$ <br>
 The jur<br>
o Det o One IE will generate a **charge cloud (CC)** of electronhole pairs
	- o **CSDA**: Continuous Slowing Down Approximation
	- $\circ$  There are two important metrics here

• 
$$
\tau_{tr}
$$
, the transit time (collection time),  $\approx \frac{d_{epi}}{\mu_e|\vec{E}}$ 

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- The junction capacitance
	- $\circ$  Determines input capacitance  $C_{in}$

$$
C_j \approx \epsilon_{Si} \frac{A_{pix}}{d_{epi}}
$$





# ticle colorers<br>
(Caeleste events<br>
(Caelester Colorers)<br>
(Caelester C PIN diode for particle counting

- Which readout methods do we pursue?
	- o **Continuous** readout
		- Bandwidth determines how quickly successive events can still be distinguished  $($ ← "dead" time)
- hich readout meth<br> **Continuous** rea<br>
 Bandwidth do<br>
can still be d<br>
 Typically, an<br>
Amplifier)<br>
⊙ Transit tir<br>
 Read noise p<br>
⊙ Flicker no<br>
∴ Need to rese<br>
 Typically, a C<br>
⊙ Transit tir<br>
 Read noise p<br>
⊙ Transit tir A determines how<br>
e distinguished ( $\leftarrow$ <br>
an RTIA (*R*-feedb<br>
it time  $\tau_{tr}$  also affe<br>
se performance af<br>
noise:  $R_{fb}$ ,  $C_{in}$ ,  $P$ <br>
r noise:  $C_{in}$ , size<br> **ampled** readout<br>
eset sometimes (=<br>
a CTIA (Charge 1<br>
it time pursue?<br>
now quickly succes<br>
d (← "dead" time)<br>
edback Transimpe<br>
affects pulse amp<br>
e affected by<br>
, P<br>
ze<br>
ut<br>
s (= "dead" time)<br>
ge Transimpedand<br>
ts slope, not step<br>
e affected by Typically, an RTIA ( $R$ -feedback Transimpedance Amplifier)
	- $\circ$  Transit time  $\tau_{tr}$  also affects pulse amplitudes!
	- Read noise performance affected by
		- $\circ$  White noise:  $R_{fb}$ ,  $C_{in}$ , P
		- $\circ$  Flicker noise:  $C_{in}$ , size
	- o **Integrated/sampled** readout
		- Need to reset sometimes (= "dead" time)
		- Typically, a CTIA (Charge Transimpedance Amplifier)  $\circ$  Transit time  $\tau_{tr}$  affects slope, not step height!
		- Read noise performance affected by
			- $\circ$  White noise:  $C_{in}$ , P
			- $\circ$  Flicker noise:  $C_{in}$ , size

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# APDs for particle counting

• Pixel is simila<br>
analog readou<br>
a PIN diode re<br>
• **Pro**<br>
⊙ Circuit solu<br>
those of P<br>
⊙ The in-dev<br>
false nega<br>
• **Con**<br>
⊙ Sensitive t<br>
Process/V<br>
(PVT) vari<br>
scale up, y<br>
⊙ Guard ring<br>
take up sig<br>
factor, incl ); the<br>similar to<br>ical to<br>duces<br> $0xide + metal  
of SPAD wa  
Oxide + metal  
of circuit wa  
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of circuit a$ • Pixel is similar to a SPAD; the analog readout circuit is similar to a PIN diode readout

• **Pro**

- o Circuit solutions identical to those of PIN diodes
- o The in-device gain reduces false negatives a lot
- **Con**
	- o Sensitive to
		- Process/Voltage/Temperature (PVT) variations, not trivial to scale up, yield sensitive
- e readout<br>solutions identical<br>of PIN diodes<br>device gain reduc<br>egatives a lot<br>ve to<br>s/Voltage/Temper<br>variations, not trivi<br>p, yield sensitive<br>ring structures car<br>increasing FN)<br>lections o Guard ring structures can take up significant space (fill factor, increasing FN)



# COUNT<br>
Transformal<br>
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Counting yield and pow<br>
Counting yield and pow<br>
Counting yield and pow<br>
Counting the crosstalk<br>
The crosstalk<br>
The crosstalk SPADs for particle counting

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Need dedicated<br>
• Pro<br>
⊙ SPADs off<br>
• Con<br>
⊙ Quenching<br>
• Longer<br>
• Conger<br>
⊙ Quest for • This m<br>
• Peak c<br>
• Higher<br>
• Larger<br>
• Guard<br>
⊙ Sensitive t Need dedicated "quench-reset" readout circuit

### • **Pro**

- o SPADs offer a very sharp timing resolution
- **Con**
	- o *Quenching* a SPAD means "dead" time
- offer a very sharp<br>
hing a SPAD mea<br>
iger "dead" time m<br>
iger quenching is<br>
for *small pixels*<br>
s means: many pixels<br>
ak currents scale v<br>
her avalanche cur<br>
ger area pixels ne<br>
ard *ring structures*<br>
ve to *PVT variatio*<br> set" readout circui<br>
narp timing resolut<br>
neans "dead" time<br>
e means higher fa<br>
is often required<br>
;<br>
y pixels (impacting<br>
le with area<br>
currents lead to m<br>
need *longer quer*<br> *need longer quer*<br> *need longer quer*<br> *need* • Longer "dead" time means higher false negative rate
	- Longer quenching is often required to reduce afterpulsing
	- o Quest for *small pixels*
		- This means: many pixels (impacting yield and power)
		- Peak currents scale with area
		- Higher avalanche currents lead to more crosstalk
		- Larger area pixels need *longer quench times*
- e rate<br>fterpulsing<br>power)<br>alk<br>(fill factor, charge<br>ield) rge sharing, increa Creasing FN) • *Guard ring structures* take up significant space (fill factor, charge sharing, increasing FN)
	- o Sensitive to *PVT variation*, not trivial to scale up (yield)

# Scintillators for particle counting

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### • **Pro**

- o Mature technology, shifts the "electron detection" challenge to "light detection"
- **Con**
	- o Hard to find scintillators with short decay and low  $eV/photon$ 
		- Hence the combination with SPADs  $\rightarrow$  One photon should be enough to detect an event
- Pro<br>
⊙ Mature ted<br>
 Con<br>
⊙ Hard to fin<br>
 Hence<br>
⊙ Secondary<br>
 Compli o Secondary photons can be spread over multiple pixels
	- Complication avoiding double counts by correlated events in neighboring pixels



## **Comparison**

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- We did a comparing study of the techniques in the previous slides with first order approximations
	- $\circ$   $\tau_{acq} = 5ns$
	- $E_{IE} \approx 10 ke^{-1}$
	- o Rate approx. 10e<sup>-</sup>/5ns
	- o Scintillator:  $LaBr_3: Ce (mono), 16eV/phot, \tau_{Sci} \approx 16ns$  [2]
	- $\circ$  Circular detector,  $\phi_{detector} = 10mm$
	- $\circ$  180 $nm$  technology parameters (average over multiple foundries), simplified analog circuits
	- $\circ$  SPAD: FF  $\approx 80\%$ , DCR  $\approx 0.3cps/\mu m^2$ , AP  $\approx 0.1\%$
	- $\circ$  APD:  $FF \approx 80\%$
	- $\circ$  PIN:  $d_{epi} \approx 10 \mu m$
	- o Power max 4W for readout

Appear to be the most practical choice



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# PIN pixel

- For the pixel, we wish to have
	- o The **largest** possible pixel (for total power consumption)
	- o A **low junction capacitance**  $C_j$  (for noise)
	- $\circ$  A **short transit time**  $\tau_{tr} \sim ns$
- For that, extra TCAD efforts were made (in collaboration with Etesian)
	- $\circ$  To avoid any badly defined behavior near the surface, we use a pinning layer
	- $\circ$  To improve  $\tau_{tr}$  and deplete the substrate, we need to apply a voltage to the backside



# PIN pixel

- Worst case  $\tau_t$ <br>near the edge<br> $\circ$  We observ<br>peaking"<br> $\circ$  Working h<br>• 3 "phas<br>• 2) Slov<br>• 3) Fast<br>well/ca • Worst case  $\tau_{tr}$  happens when the IE lands near the edge of the pixel
- when the IE lands<br>|<br>simulation "double<br>|<br>charge cloud<br>|
|ackside to deep |
|
|deep N to No We observe in TCAD simulation "double peaking"
	- o Working hypothesis:
		- 3 "phases" of the charge cloud
		- 1) Fast drift from backside to deep N
		- 2) Slower drift/diffusion along deep N
- egge of the pmail<br>serve in TCAD sing"<br>g hypothesis:<br>hases" of the cha<br>Fast drift from bacl<br>Slower drift/diffusic<br>Fast drift from dee<br>l/cathode • 3) Fast drift from deep N to Nwell/cathode



- A test chip was made to verify results
	- o Backside illuminated
	- $\circ$  ~45 variants
		- Focus on CTIA-based PIN variants
		- Some RTIA-based variants also available
- A test chip wa<br>
⊙ Backside i<br>
⊙ ~45 variar<br>
 Focus<br>
 Some<br>
 Fast R<br>
photoc<br>
 Supported me<br>
⊙ Equivalent<br>
⊙ Digital rea de murimated<br>riants<br>cus on CTIA-based<br>me RTIA-based vart<br>RTIAs dedicated<br>tocurrent<br>measurements<br>lent Time Samplin<br>readout method fo<br>24 verify results<br>I variants also ava<br>ated to measurem<br>s<br>S<br>pling<br>d for FP and FN nts<br>available<br>ement of<br>N • Fast RTIAs dedicated to measurement of photocurrent
- Supported measurements
	- o Equivalent Time Sampling
	- o Digital readout method for FP and FN



- 
- 
- 
- Dummy pixel
- 

- Emulating an<br>
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 Laser |<br>
 Emulat<br>
⊙ Las<br>
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→<br>
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 Emulat<br>
⊙ A re • Emulating an **incident electron** (IE)
	- o Use a laser
		- Laser pulse width should be negligible compared to  $\tau_{tr}$
		- Emulating the small charge cloud
			- o Laser spot should be focused
				- $\rightarrow$  Maybe possible with optics, but likely not easy
				- $\rightarrow$  We attempt to use pinholes in a backside metal
			- o Wavelength should be chosen to have a similar penetration depth as CSDA of an IE
- er pulse width show<br>ulating the small d<br>Laser spot should<br> $\rightarrow$  Maybe possib<br> $\rightarrow$  We attempt to<br>Wavelength shoul<br>penetration depth<br>Optical power show<br>same number of e<br>silicon<br>ulating noise<br>A real IE-caused o<br>noise which is ectron (IE)<br>should be negligit<br>all charge cloud<br>buld be focused<br>sible with optics, I<br>t to use pinholes i<br>nould be chosen to<br>pth as CSDA of a<br>should be attenua<br>of electrons are go<br>ed charge cloud w<br>typically smaller t ligible compared t<br>d<br>x<br>s, but likely not ea<br>es in a backside m<br>n to have a simila<br>of an IE<br>nuated such that t<br>e generated inside o Optical power should be attenuated such that the same number of electrons are generated inside the silicon
	- Emulating noise
		- o A real IE-caused charge cloud will exhibit Fano noise which is typically smaller than photon shot noise!



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- Support for **analog measurements**
- Support for ar<br>
⊙ Measuring<br>
straightfor<br>
 Measu<br>
"distort<br>
⊙ **Equivaler<br>
•** Open t<br>
a point<br>
 Use m<br>
buffer t<br>
⊙ Lar<br>
ανε<br>
exp<br>
 Slightl<sub>)</sub><br>
experir<br>
 You ca o Measuring high bandwidths on-chip is not straightforward
	- Measurement circuitry will always "distort" due to parasitic capacitances
	- o **Equivalent Time Sampling** [3]
		- Open the S&H switch with low jitter at a point  $t_{sh}$ , measure slowly after
		- Use minimum  $C_{S\&H}$ , and very small buffer to minimize added capacitance
- ring riight bandwider<br>tforward<br>asurement circuitr<br>tort" due to parasi<br>**ilent Time Sampl**<br>an the S&H switch<br>pint  $t_{sh}$ , measure and<br>experiment<br>alexperiment<br>subset and review and review<br>intly shift  $t_{sh}$  and refinent<br>an t surements<br>widths on-chip is r<br>uitry will always<br>rasitic capacitance<br>**npling** [3]<br>itch with low jitter<br>ire slowly after<br> $_{H}$ , and very small<br>added capacitanc<br>se, so might want<br>nultiple identical<br>nd repeat the  $\circ$  Large  $kTC$  noise, so might want average over multiple identical experiments
	- Slightly shift  $t_{sh}$  and repeat the experiment
	- You can then reconstruct the waveform



- Support for **digital measurements**
- Support for **di**<br>
⊙ Measuring<br>
laser pulse<br>
 FN: Ap<br>
was de<br>
⊙ Ass<br>
 FP: Da<br>
CTIA-t<br>
 Shoulc<br>
functio<br>
⊙ Laser shot<br>
 We wil<br>
 Or use o Measuring of false positives and false negatives using laser pulses
	- FN: Apply/inject pulses and find out whether an event was detected
		- o Assess mismatch variation
	- FP: Dark current will always cause a trigger with CTIA-based variants if you wait long enough!
- ring or raise positivalses<br>Apply/inject pulse<br>is detected<br>Assess mismatch<br>Dark current will<br>A-based variants<br>buld be able to rec<br>ction<br>shot noise vs. Fan<br>will measure a we<br>use actual particle<br>ase actual particle **urements**<br>sitives and false r<br>ulses and find out<br>tch variation<br>will always cause a<br>nts if you wait long<br>reconstruct a prok<br>Fano noise<br>a worse case, but<br>icles... Se negatives using<br>
Se a trigger with<br>
Se a trigger with<br>
Se a trigger with<br>
Se a trigger with<br>
Se modele<br>
Sut can be modele • Should be able to reconstruct a probability density function
	- o Laser shot noise vs. Fano noise
		- We will measure a worse case, but can be modeled
		- Or use actual particles…



- Example result
	- o No pixel yet, instead we use capacitive **charge injection**
		- CTIA example variant
		- $Q_{injected} \approx 7.5 ke^{-1}$
		- $P \approx 180uW$
		- Spikes are caused by external clock edges
		- Time resolution  $\sim 150 \text{ps}$

Voltage (V)

- Example resu<br>
⊙ No pixel ye<br>
capacitive<br>
 CTIA ∈<br>
  $Q_{inject}$ <br>
  $P \approx 18$ <br>
 Spikes<br>
externa<br>
 Time resterna<br>
 Time resterna<br>
 No measurem<br>
pulses<br>
 No FP/FN me<br>
with laser puls Bridget, instead we<br>ive **charge inject**<br>A example varian<br>iected  $\approx 7.5ke^{-1}$ <br>180*uW*<br>kes are caused by<br>semal clock edges<br>ie resolution ~150<br>rement yet with la<br>measurement yet<br>pulses) • No measurement yet with laser pulses
- we use<br> **ection**<br>
iant<br>
d by<br>
les<br>
150*ps*<br>
c 50<br>
c 50<br>
c 50<br>
yet (also<br>
yet (also • No FP/FN measurement yet (also with laser pulses)



## References

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- [1] Wolfgang W. Gärtner. "Depletion-Layer Photoeffects in Semiconductors." *Physical Review*, 116(1):84–87, October 1959.
- [1] Wolfgang<br>116(1):84–87<br>• [2] E. V. D. va<br>properties of I<br>Instruments 8<br>Associated Ed<br>• [3] K. Rush, D<br>Packard Journ er, eccesor recest<br>
Control Caeler, P. Dors<br>
of LaBr3 : Ce3+ c<br>
ts & Methods in Pl<br>
d Equipment", 486<br>
n, D. J. Oldfield "A<br>
purnal, vol. 37, Nc<br>
24 "Depletion-Layer<br>959.<br>Dorenbos, C. W. E<br>3+ crystals: fast, et<br>1 Physics Researd<br>486:254-258, 200:<br>I "A Data Acquisiti<br>No. 4, pp. 4- 11, ver Photoeffects in<br>V. E. van Eijk, K. V<br>t, efficient and hig<br>earch Section A-A<br>2002.<br>isition System for<br>1, April 1986. ts in Semiconduct<br>K. W. Kramer and<br>high-energy-resol<br>A-Accelerators Sp<br>for 1-GHz Digitizir and H. U. Gudel. "<br>solution scintillate<br>Spectrometers De<br>tizing Oscilloscope cal Review,<br>el. "Scintillation<br>lators. Nuclear<br>s Detectors and<br>cope," Hewlett-• [2] E. V. D. van Loef, P. Dorenbos, C. W. E. van Eijk, K. W. Kramer and H. U. Gudel. "Scintillation properties of LaBr3 : Ce3+ crystals: fast, efficient and high-energy-resolution scintillators. Nuclear Instruments & Methods in Physics Research Section A-Accelerators Spectrometers Detectors and Associated Equipment", 486:254-258, 2002.
- [3] K. Rush, D. J. Oldfield "A Data Acquisition System for 1-GHz Digitizing Oscilloscope," Hewlett-Packard Journal, vol. 37, No. 4, pp. 4- 11, April 1986.

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# Caeleste<br>Caeleste<br>Caeleste<br>Caeleste nk you Caeleste<br>Caeleste<br>Caeleste **Thank you**

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