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Ultimate 3D for a Pixel Detector - Tests of X-Rays Detection

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AGH

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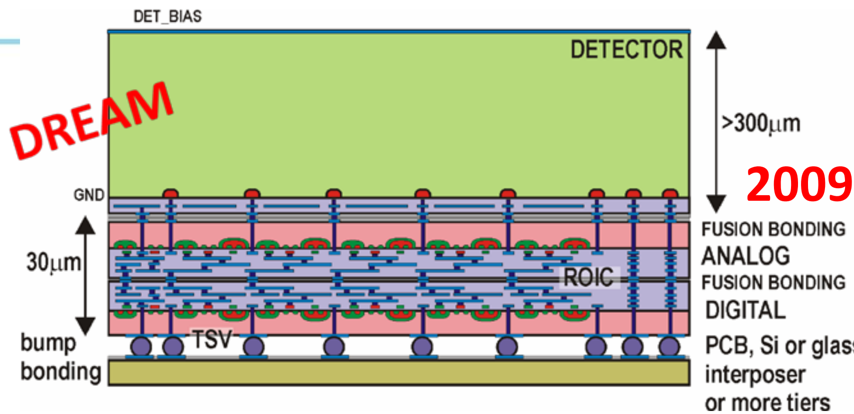
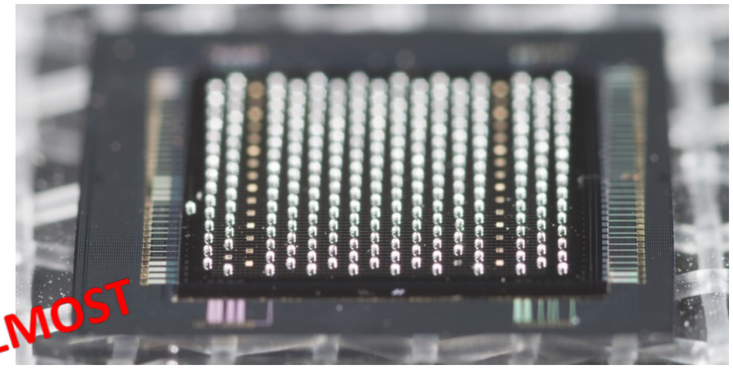
Outline:

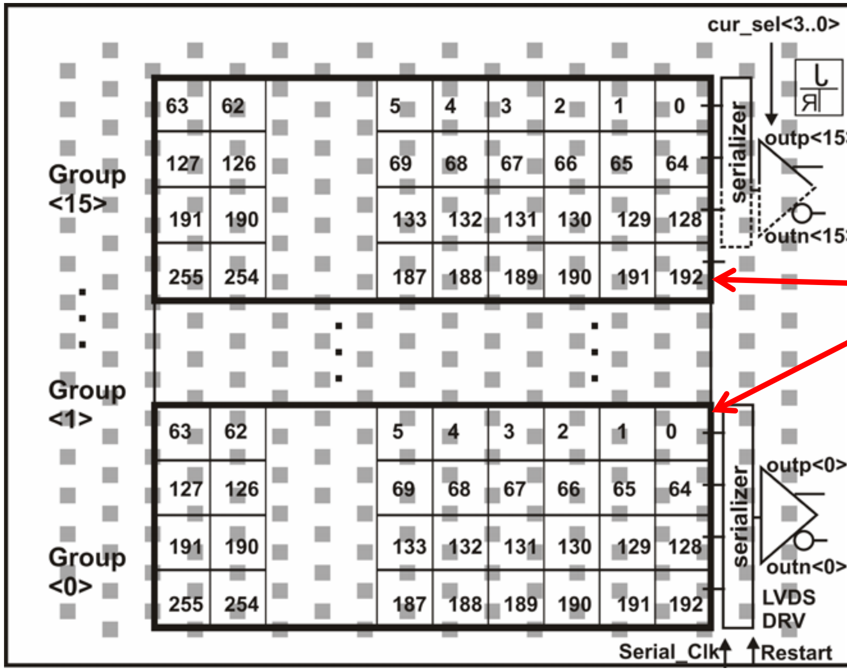
- Ultimate 3D-integrated VIPIC1 chip structure
  - Update on 3D fabrication processing for VIPIC
    - W-2-W: ASIC stacking
    - D-2-D: sensor - ASIC b-bonding
    - D-2-W: ASIC - sensor fusion bond
    - D-2-PCB: 3D stack b-bonding
  - Test results of VIPIC
    - Fusion bonded
      - Front side illumination
      - Back side illumination
      - Ultimate b-bonded on PCB
- Conclusions





VIPIC1

VIPIC1 (prototype) counts hits in every pixel and reads out the # of hits, and pixel addresses in a dead timeless manner,



Active area: $5120 \times 5120\ \mu m^2$, chip: $6.3 \times 5.5\ mm^2$

Matrix of 64×64 pixels divided into 16 group of 4×64 pixels read through one LVDS buffer

Sparsification engine selects hit pixels in every group for readout

Only digital information read out (~150 ns /hit pixel)

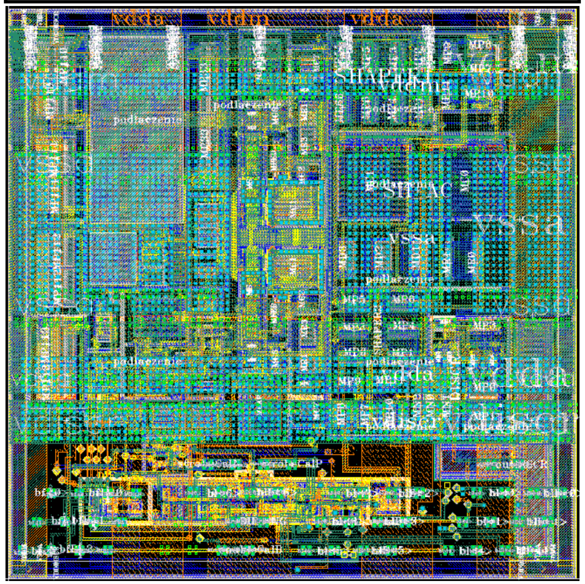
PROCESS VIPIC

"Vertically Integrated Circuits at Fermilab", IEEE Transaction on Nuclear Science, vol. 57, no. 4, (2010), pp. 2178-2186
"VIPIC IC - Design and Test Aspects of the 3D Pixel Chip", Proceedings of NSS & MIC, Knoxville, TN, USA, October 2010
" Design and Tests of the Vertically Integrated Photon Imaging Chip", IEEE Trans. on Nuclear Sci., vol. 61, no. 1, (2014), pp. 663-674
"Results of Tests of Three-Dimensionally Integrated Chips Bonded to Sensors", accepted for IEEE Transaction on Nuclear Science

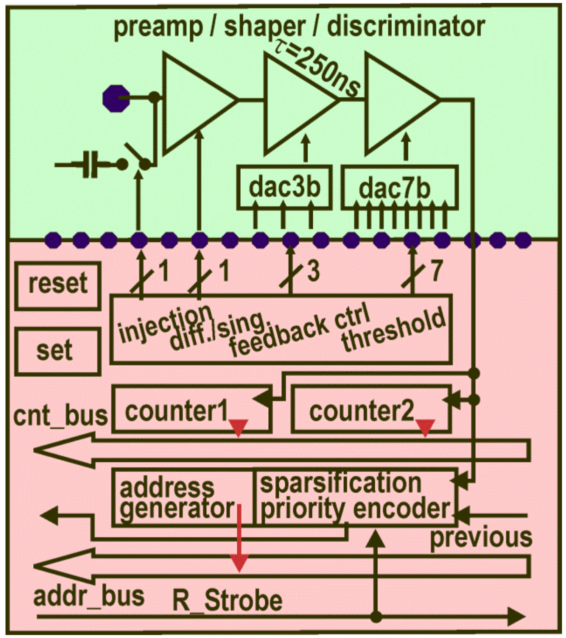
"Recent Results for 3D Pixel Integrated Circuits Using Copper-Copper and Oxide-Oxide Bonding", PoS(VERTEX 2013)032
"Performance of Three Dimensional Integrated Circuits Bonded to Sensors", PoS(VERTEX 2014)XXX

ANALOG

280 transistors

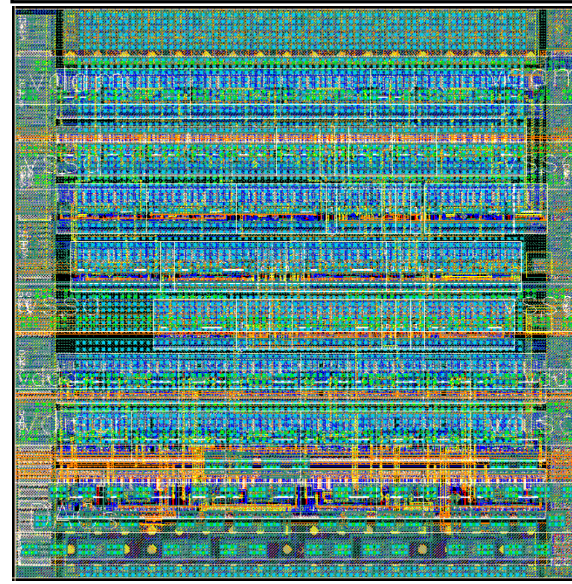


INTERFACE



DIGITAL

1400 transistors



- **Single ended or pseudo-differential CSA-shaping filter-discriminator – design goals:** shaping time τ_p=250 ns, power ~25 μW / analog pixel, noise <150 e^- ENC, gain(C_{feed}=8fF) = ~100mV/8keV (optimized for 8 keV in Si - linear up to 3×8 keV)
- **1 threshold discriminator**
- **10 bit/pixel DAC adjustments**

12-bit for configuration
7-bit trim offset, 3-bit trim R_f, single/dif mode, CAL enable

2-lines for CAL circuits

discriminator output

Doubled bond pads for each signal
Power suplies tied between tiers

- **in-pixel 1-stage pipe-line logic**
- **distributed sparsifier: 8 bit priority encoder, pixel readout selector, pixel address generator and counter output**
- **2×5 - bit long counters**
- **configuration registers: single bit / pixel** (pixel SET, pixel RESET) and 12 bit DAC and configuration (calib., singl./diff.)

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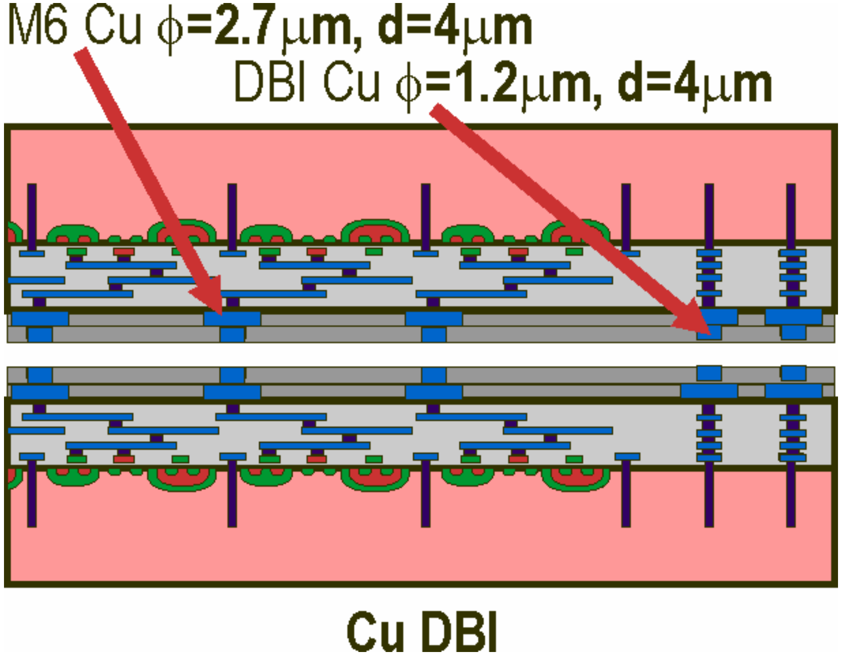
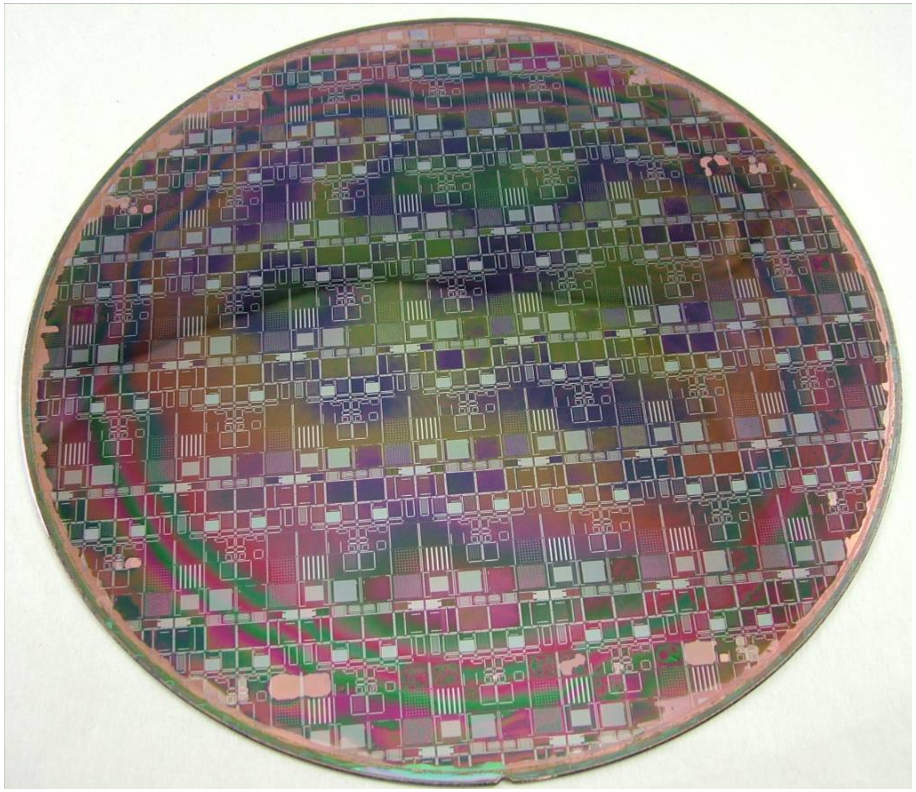
Processing: W-2-W ASIC stacking



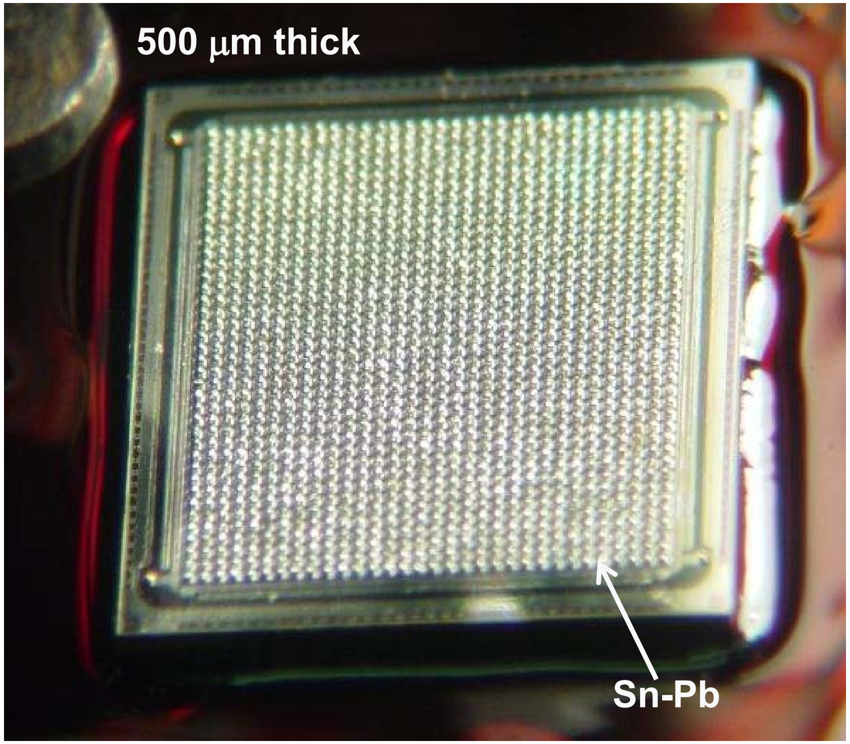


Cu-DBI (oxide-oxide fusion bonding) used for bonding tiers of 3D VIPIC

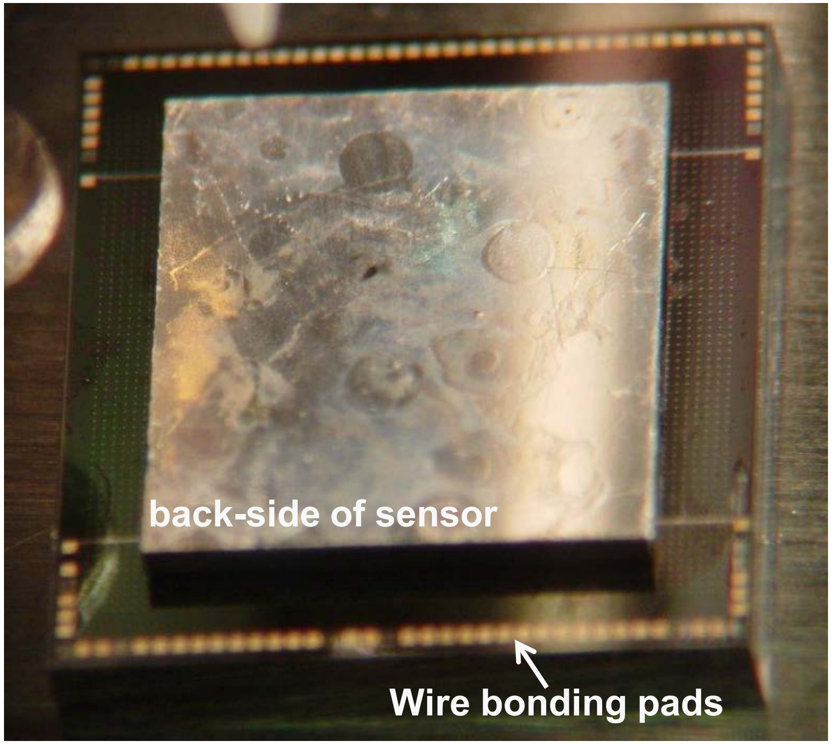
- no pressure requried and self propagating from initial contact point
- can be reworked for a short time after initial bonding

8" bonded wafer pair with top wafer thinned to expose 6μm TSVs (6μm of silicon left of the top wafer)

Processing: D-2-D sensor - ASIC bump-bonding

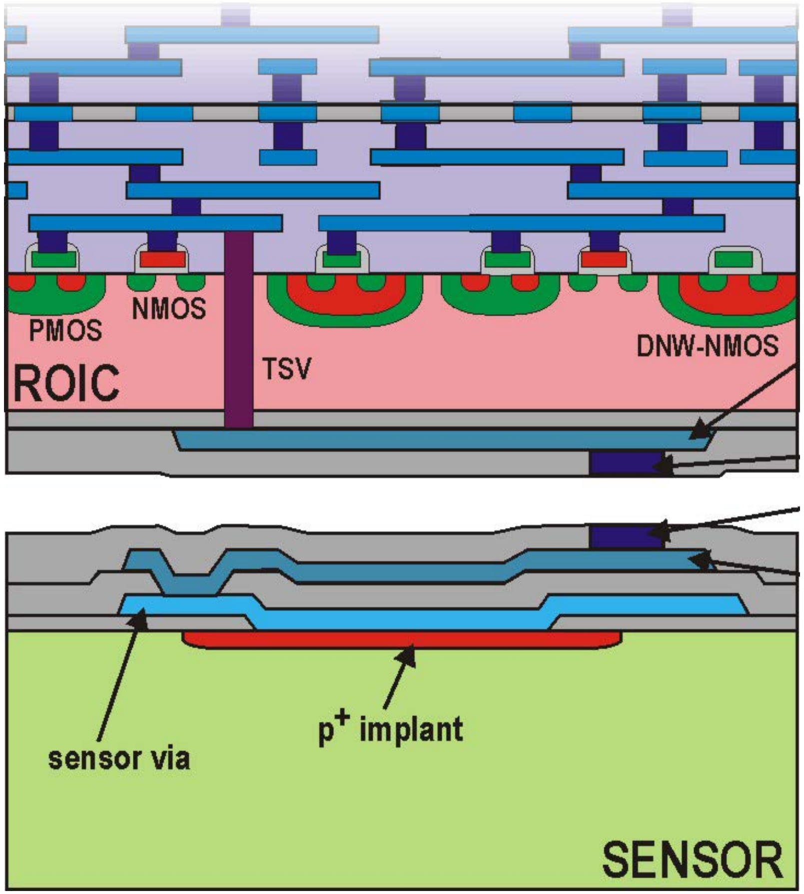


- 100 μm pitch HPK pixel baby-sensor
- Sn-Pb bumps deposition on a single die with ENIG UBM on Al substrate pads (by CVInc.) – pads ϕ=60 μm
- UBM also deposited on VIPIC



- 300 μm thick baby-sensor on top of VIPIC (75 μm bump, post reflow gap at 45 μm to 50 μm prior to addition of underfill)
- Optimization of the Ni-Au deposition = ~100% of pads retaining UBM and bumps

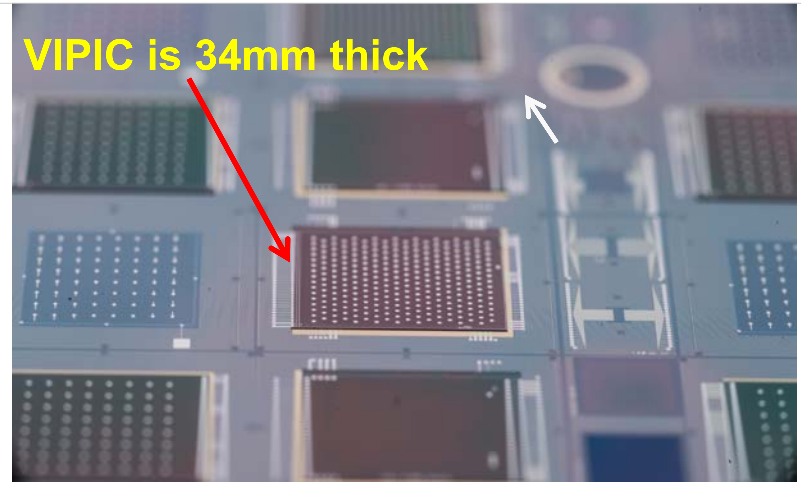
Processing: D-2-W ASIC - sensor fusion bonding



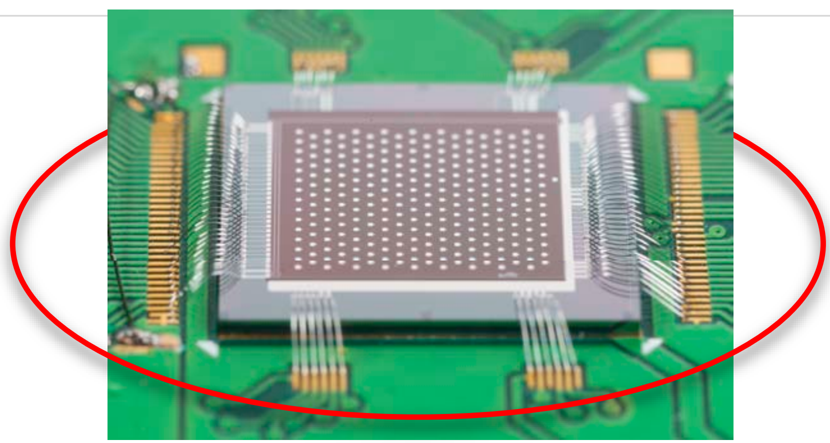
Ni-DBI (oxide-oxide fusion bonding) with DBI post ϕ=5 mm,

top-2-bottom: 50nm nitride, 1µm oxide, 300nm Al, 1µm oxide + 700nm DBI and 700nm DBI + 1µm oxide, 300nm Al, 1um oxide, 300nm thermal oxide

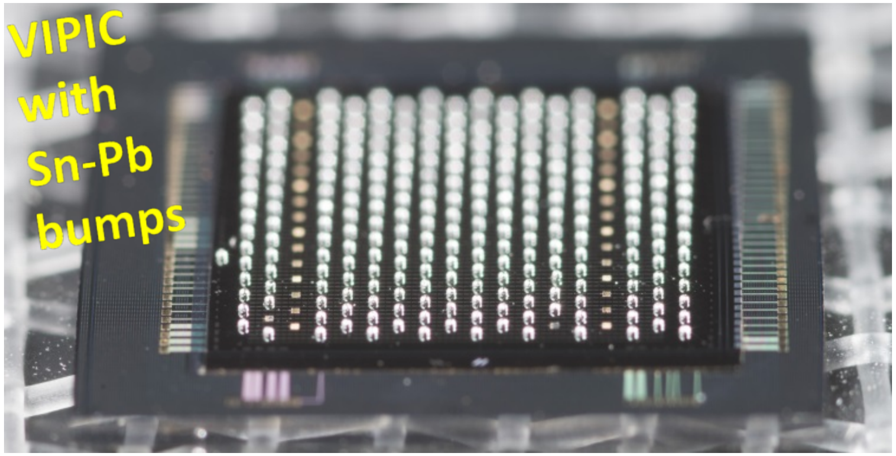
die on 6” 500µm thick sensor wafer



allows back and front -side illumination

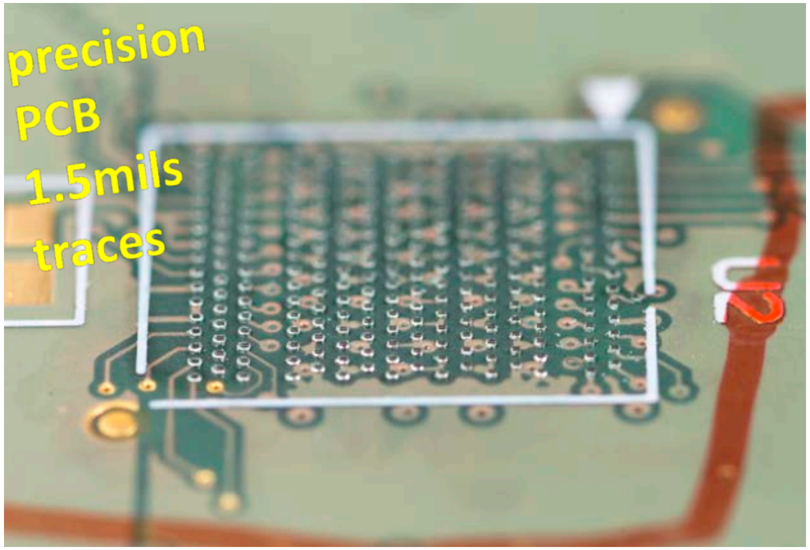


Processing: D-2-PCB 3D stack b-bonding



Sn-Pb bumps deposition on a single 3D assembly with ENIG UBM on Al substrate pads (by CVInc.)
– square pads a=100 μm, 279 pads on 320μm pitch (staggered layout)
– challenge for design on FR-4 PCB 1.5 mils traces (it would be easier on ceramic or on silicon interposer - future)

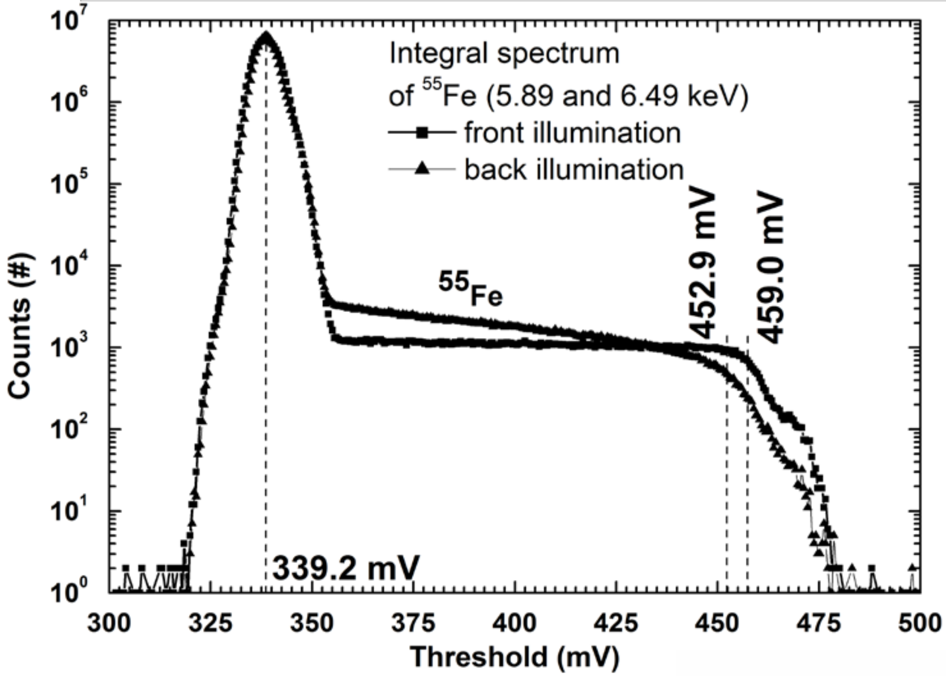
'ultimate 3D VIPIC1'

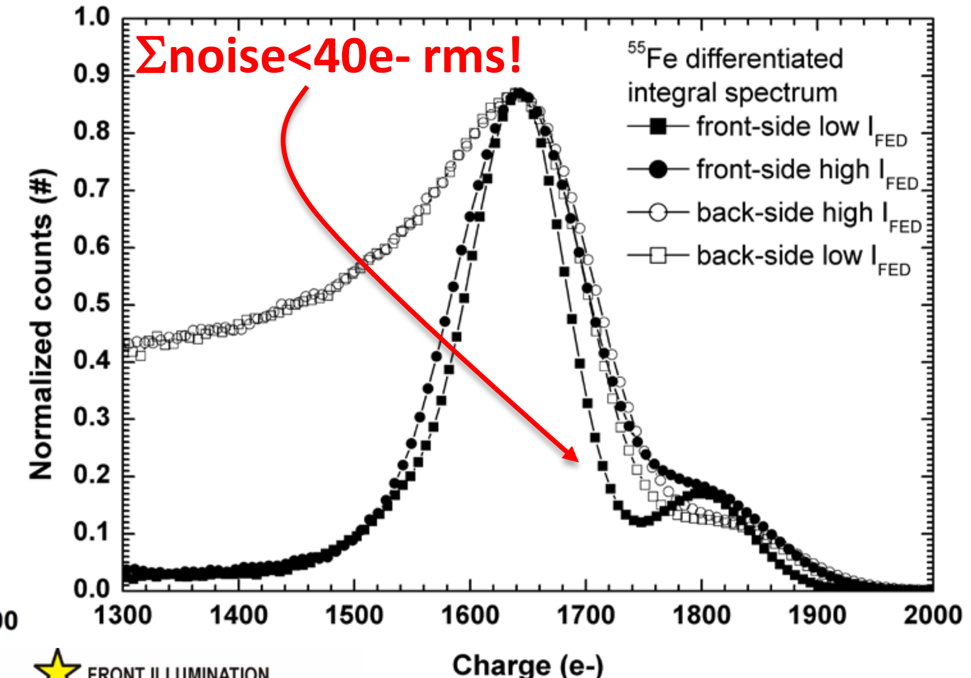


underfill epoxy to stabilize VIPIC on flexing substrate

Results: reference X-ray source spectra

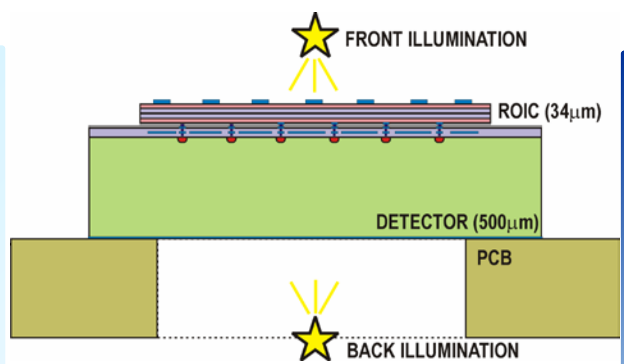
thin die and access through traces on sensor ➔ front and back illumination





integral E spectra of ^{55}Fe

front and back illumination of 500 μm thick fully depleted (V_{dep}=170V) Si sensor with fusion bonded VIPIC1 (threshold scan @ ΔV=500μV)



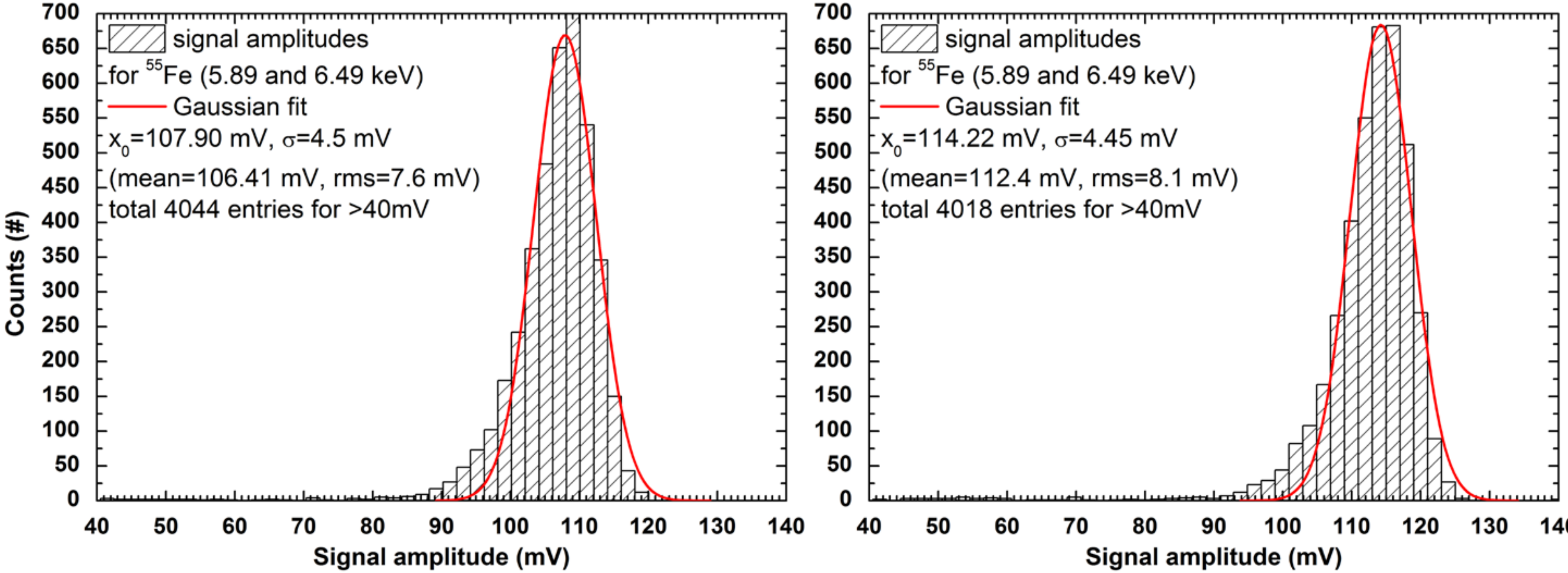
E spectra of ^{55}Fe

(amplitudes scaled to expected spectral peaks)

front and back illumination with varied resistances in feedback of preamplifier

Results: gain* from reference X-ray source

back and front illumination



BACK ILLUMINATION

Q-2-V gain = 65.18 $\mu V/e^-$ ± 2.74 $\mu V/e^-$

<1.3 % of pixels not connected or having lower gain for other reasons

FRONT ILLUMINATION

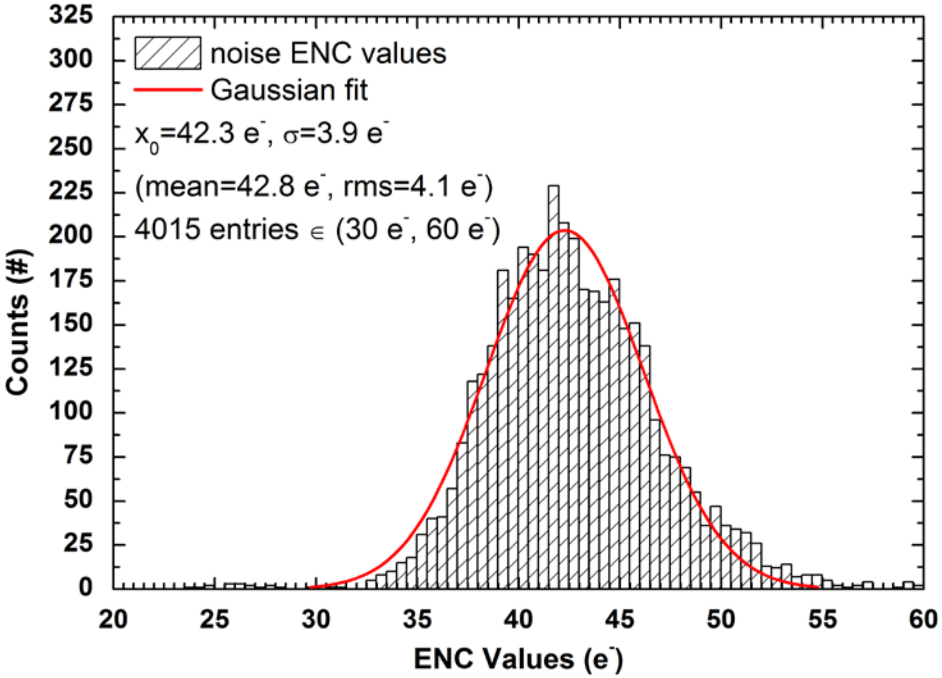
Q-2-V gain = 69.64 $\mu V/e^-$ ± 2.71 $\mu V/e^-$

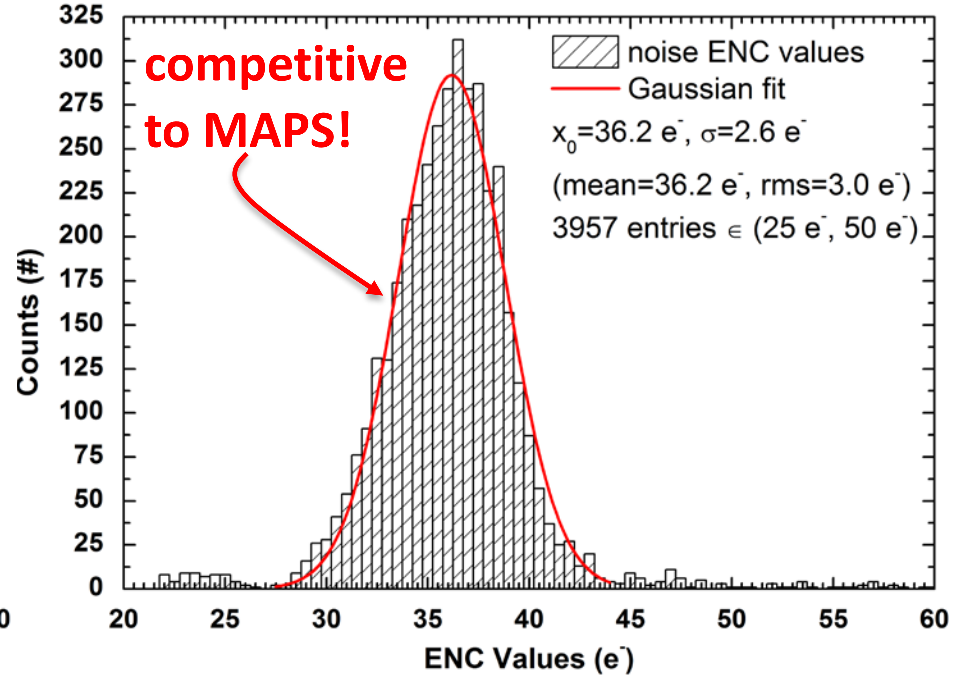
<1.9 % of pixels not connected or having lower gain for other reasons

*gain calculated through adaptive procedure of numerical differentiation of integral spectra

Results: noise from calibrated gain

front illumination with small and large feedback resistance in preamplifier





SMALL FEEDBACK RESISTANCE

$ENC=42.3e^- \pm 3.9e^-$

symmetrical noise distribution with

<1.9 % of pixels outside of $\pm 3\ \sigma$ range

LARGE FEEDBACK RESISTANCE

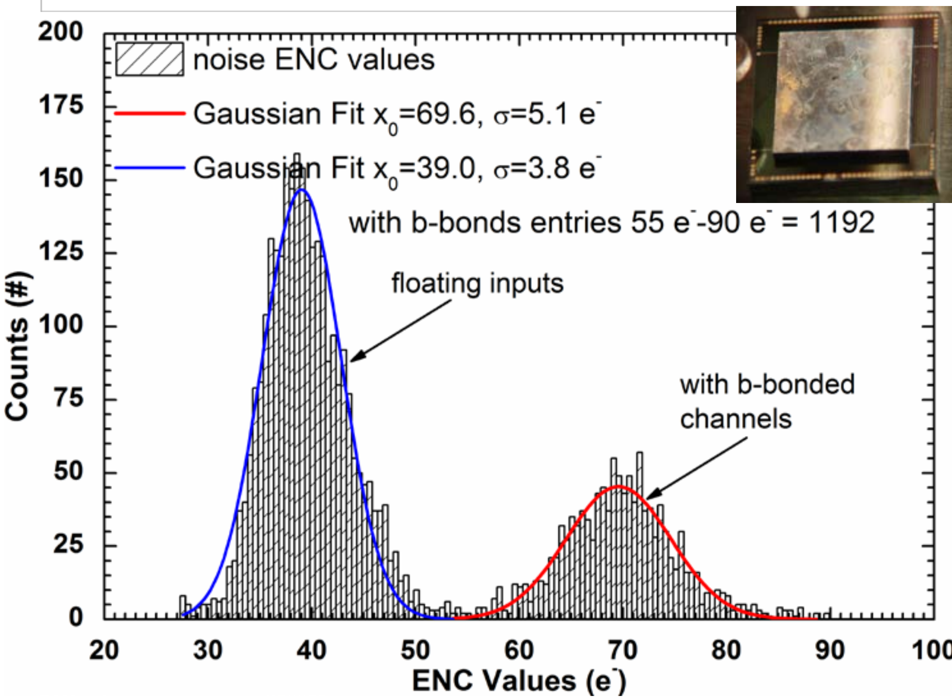
$ENC=36.2\ e^- \pm 2.6\ \mu V/e^-$

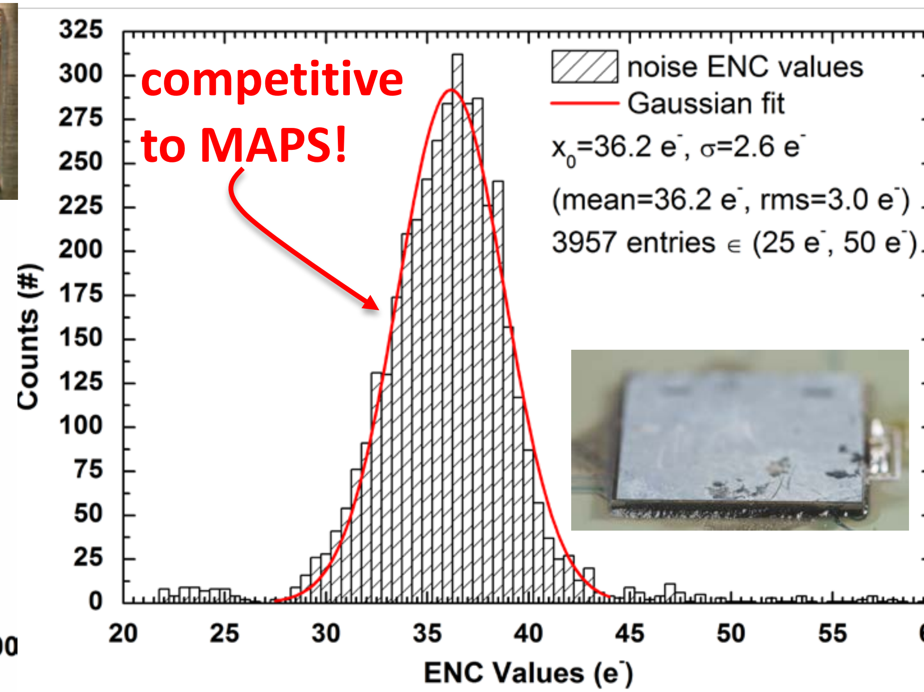
symmetrical noise distribution with

<3.4 % of pixels outside of $\pm 3\ \sigma$ range

Results: noise comparison fusion-bonded vs bump-bonded

Bump-bonded VIPIC1 pitch 100μm vs. 80μm for fusion-bonded, nevertheless …





32 × 38 pixels bonded, 2880 pixels floating

bump-bonded: ENC=69.6 e^- ± 5.1 μV/e^-

larger input capacitance = larger noise, lower gain and more dispersions

LARGE FEEDBACK RESISTANCE

ENC=36.2 e^- ± 2.6 μV/e^-

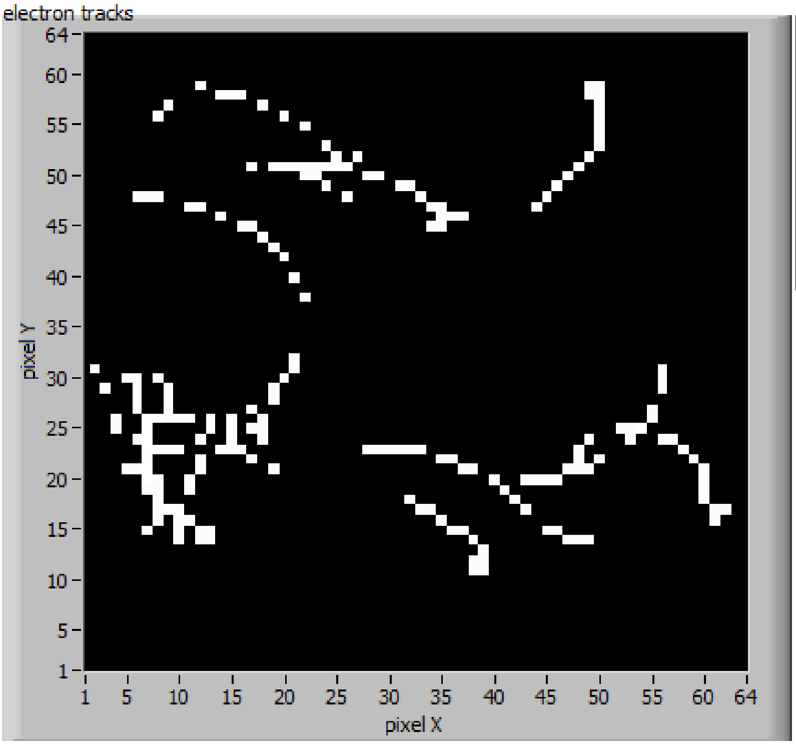
symmetrical noise distribution with <3.4 % of pixels outside of ±3 σ range

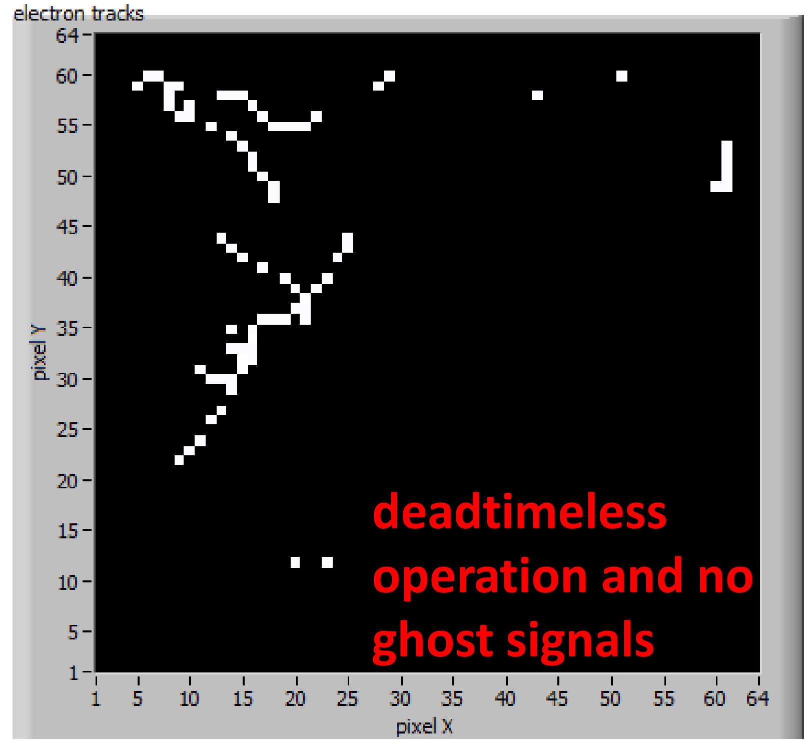
ENC on fusion bonded device is close to that measured for floating inputs!

ENC=40e^- C_{in}<20fF, ENC=70e^- C_{in}>80fF

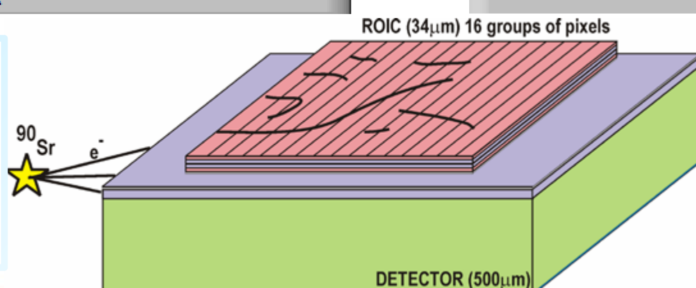
Sparsified readout

tracks of 0.546 MeV (endpoint) electrons from ^{90}Sr in fully depleted (V_{dep}=170V) Si sensor with fusion bonded VIPIC1 (perpendicular to groups)





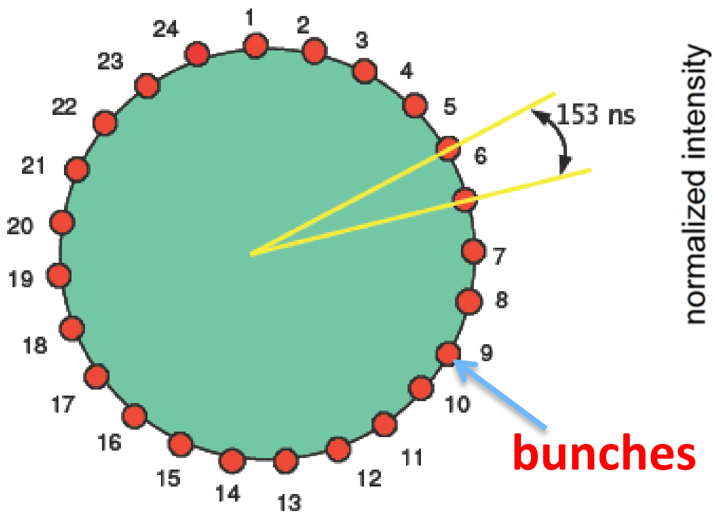
Superposition of selected 13 frames acquired @ Δt=2.7μs (max. 24 hits/group)

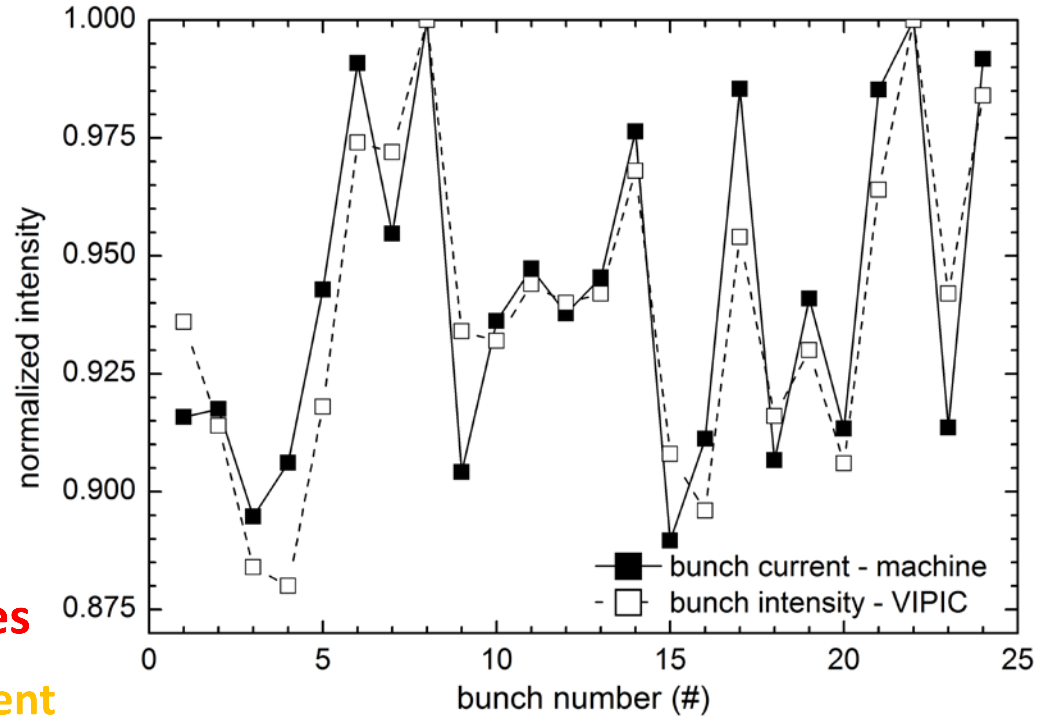


Superposition of 13 frames; each frame is directly next to the respective one used to the left.

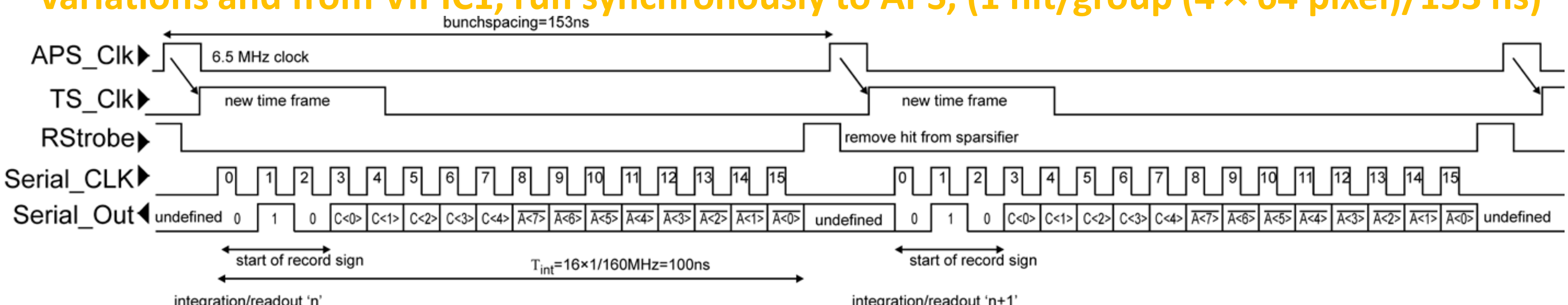
Results: APS 10keV X-ray beam

fill pattern: 24 bunches spaced by 153ns, **tests with direct beam on 'ultimate 3D VIPIC1'**





X-ray intensity from b-b e⁻ beam current variations and from VIPIC1, run synchronously to APS, (1 hit/group (4 × 64 pixel)/153 ns)



Conclusions

- Conclusive demonstration of the capabilities of 3D technology applied to pixel detectors has been reached!
- Shown parameters are better than for bump-bonded devices and competitive with MAPS (in term of noise).
- Analyses of data from XCS experiments performed in July and October 2014 are underway (first capture of samples' dynamics on a scale of tens of μs with a 2D detector)
- BES funded project (3 labs collaboration BNL-FNAL-ANL) to build a 1M-pixel camera for XCS experiments using 3D-IC technology
- Ackonwledgments: Alec Sandy, Eric Dufresne, Suresh Narayanan, John Weizeorick, David Kline (beam tests at the APS at ANL); many thanks to Albert Dyer (board assembly)

- Tezzaron and Ziptronix, as the 3D technology providers.
- The greatness of 3D-IC consortium (17 partners from USA, France, Italy, Germany, Poland and Canada), enthusiasm and exchange of information for common goals were fundamental.

Tezzaron SEMICONDUCTOR

ziptronix

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