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

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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 (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 $64 \times 64$ pixels divided into 16 group of $4 \times 64$ 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)

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“VIPIC IC - Design and Test Aspects of the 3D Pixel Chip“, Proceedings of NSS & MIC, Knoxville, TN, USA, October 2010


“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
280 transistors

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

1400 transistors

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

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

Doubled bond pads for each signal
- Power supplies tied between tiers

Discriminator output

- 2-lines for CAL circuits
Processing: W-2-W ASIC stacking

Cu-DBI (oxide-oxide fusion bonding) used for bonding tiers of 3D VIPIC
- no pressure required 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 $\phi=60$ 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 $\phi=5$ mm,
top-2-bottom: 50nm nitride, 1$\mu$m oxide, 300nm Al,
1$\mu$m oxide + 700nm DBI and 700nm DBI + 1$\mu$m oxide,
300nm Al, 1um oxide, 300nm thermal oxide

die on 6” 500$\mu$m thick sensor wafer

VIPIC is 34mm thick

allows back and front -side illumination
Sn-Pb bumps deposition on a single 3D assembly with ENIG UBM on Al substrate pads (by CVInc.)
- square pads $a=100\ \mu m$, 279 pads on $320\mu m$ 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)
Results: reference X-ray source spectra

integral E spectra of $^{55}$Fe
front and back illumination of 500 μm thick fully depleted ($V_{\text{dep}}=170V$) Si sensor with fusion bonded VIPIC1
(threshold scan @ $\Delta V=500\mu V$)

Σnoise<40e- rms!

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$^-$ $\pm$ 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$^-$ $\pm$ 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 = 42.3 e⁻ ± 3.9 e⁻
- Symmetrical noise distribution with <1.9 % of pixels outside of ±3 σ range

**Large Feedback Resistance**
- ENC = 36.2 e⁻ ± 2.6 μV/e⁻
- Symmetrical noise distribution with <3.4 % of pixels outside of ±3 σ range

Competitive to MAPS!
Results: noise comparison fusion-bonded vs bump-bonded

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

- Bump-bonded: ENC=69.6 e⁻ ± 5.1 μV/e⁻
  - 32 x 38 pixels bonded, 2880 pixels floating
  - Larger input capacitance = larger noise, lower gain and more dispersions
- Fusion-bonded: ENC=36.2 e⁻ ± 2.6 μV/e⁻
  - With b-bonds entries 55 e⁻-90 e⁻ = 1192
  - 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⁻ Cᵢᵣ<20fF, ENC=70e⁻ Cᵢᵣ>80fF

LARGE FEEDBACK RESISTANCE
ENC=36.2 e⁻ ± 2.6 μV/e⁻

G.Deptuch | Ultimate 3D for a Pixel Detector - Tests of X-Rays Detection
Sparsified readout

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

Superposition of selected 13 frames acquired @ $\Delta t=2.7\mu s$ (max. 24 hits/group)

deadtimeless operation and no ghost signals

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
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