First results with novel pixel detectors based on wafer-wafer bonding

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Introduction

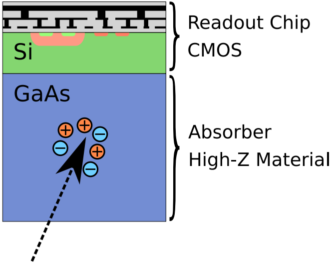
How to create hetero-structure semi-conductor pixel detectors without bump bonding?

- Focus on X-Ray applications

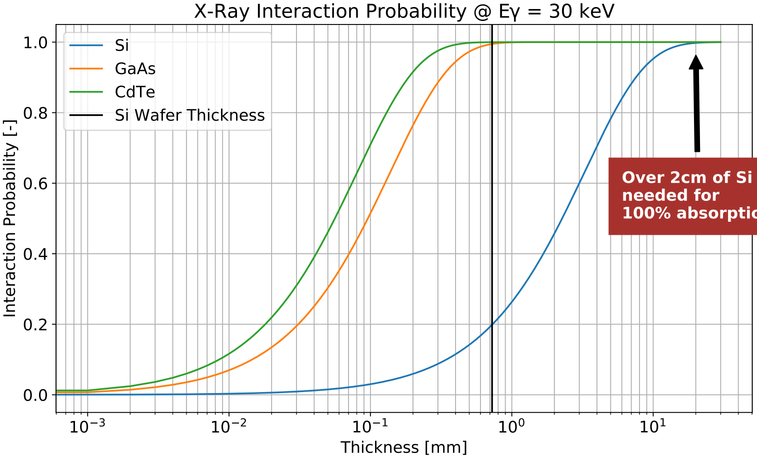
$$E_\gamma = 1 \text{ to } 100 \text{ keV}$$

- The general principle is applicable to any type of semiconductor particle detector.

Pixel Cross Section

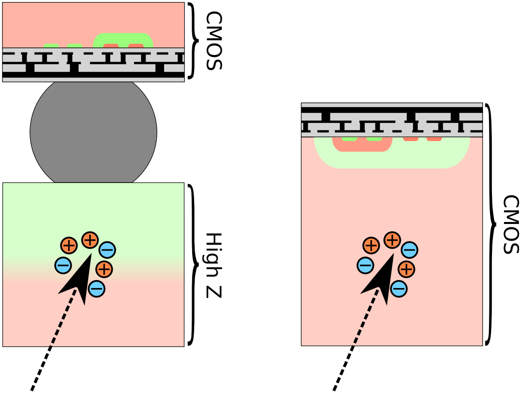


Mammography X-Ray Absorption



Over 2cm of Si needed for 100% absorption

Hybrid vs. Monolithic Design



Hybrid

Monolithic

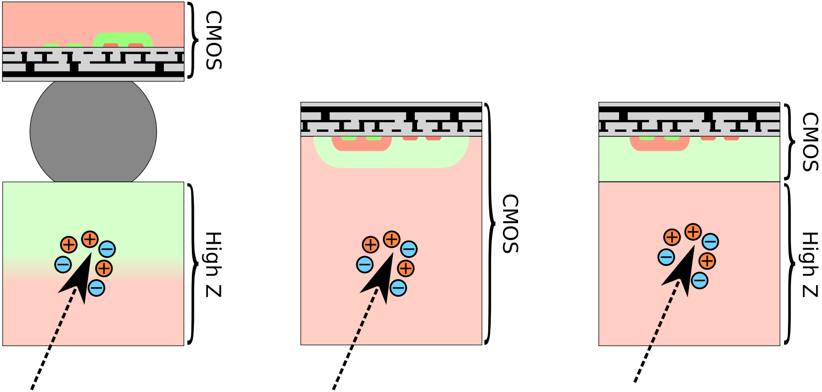
🟩 N Doped

🟥 P Doped

⬛ Bump Bond

▨ Metal Layers

Hybrid vs. Monolithic vs. Bonded Design



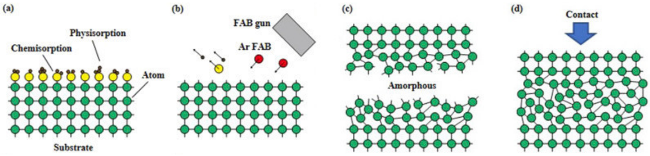
Hybrid

Monolithic

Covalent Bond

🟩 N Doped 🟥 P Doped ■ Bump Bond ▨ Metal Layers

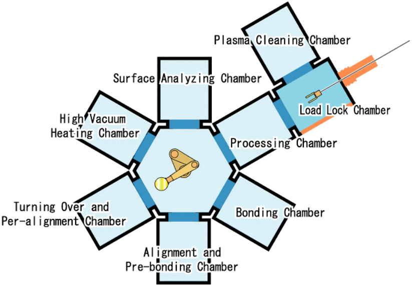
Low Temperature Covalent Bonding Principle



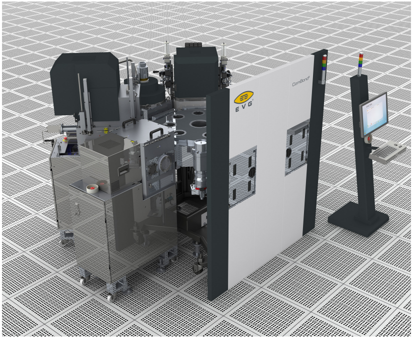
From [1]

- Oxide removal via ion beam or plasma sputtering.
- Re-oxidation inhibited via ultra high vacuum.
- No high temperature annealing necessary.

Bonding Machine



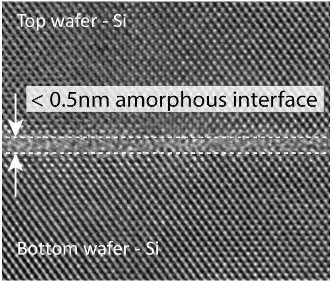
From [2]



From [3]

- Pioneered by the T. Suga group at University of Tokyo [2].
- Commercial machines available (e.g. from EV Group [3])

Bonding Interface



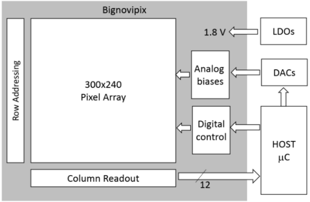
From [4]

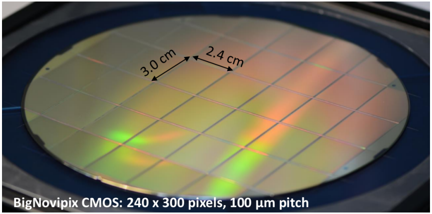
- Surface activation leads to a **thin amorphous layer**.
  - Can potentially be reduced via low temperature annealing.
- Misalignment of the crystal structure leads to **trap states** at the interface.
  - Density of the order of $10^{13} \frac{1}{\text{cm}^2}$

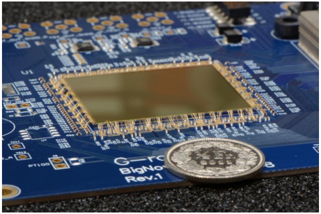
G-ray - Latenium™ Detector

Industry Partner:

G-ray Switzerland SA
Hauterive / Neuchâtel
`https://www.g-ray.ch/`



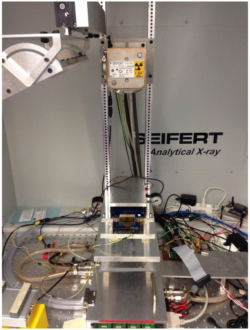




From [4]

First Latenium^{TM} Test Campaign

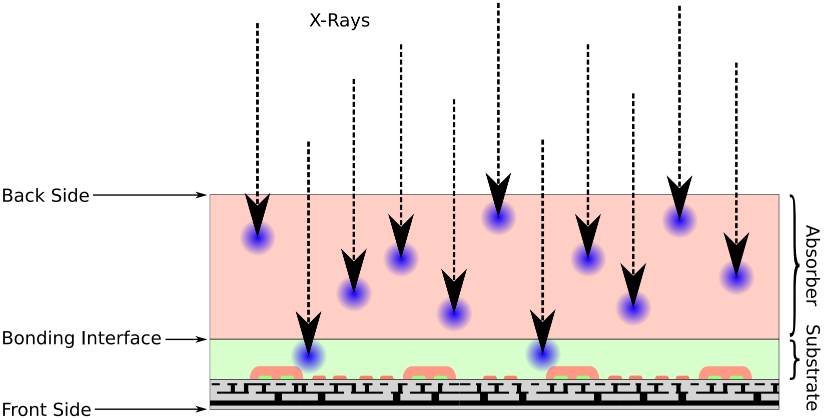
During 2019 we received and tested four Si:Si samples.



ETHZ IPA X-Ray Chamber

- The Latenium^{TM} detector is a highly integrated system
  - The current prototypes do not expose the analog signals.
- Therefore the bonding interface can not directly be probed
  - Leakage current measurements give some info about the DC properties of the interface.
  - Photon detection efficiency can give information about the transparency of the interface.

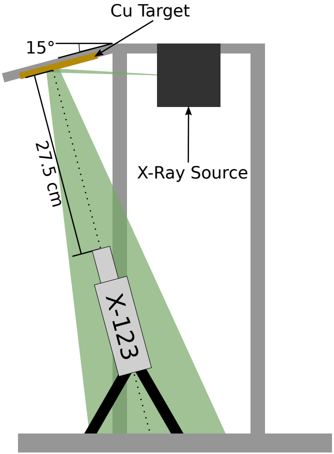
Substrate Efficiency Analysis

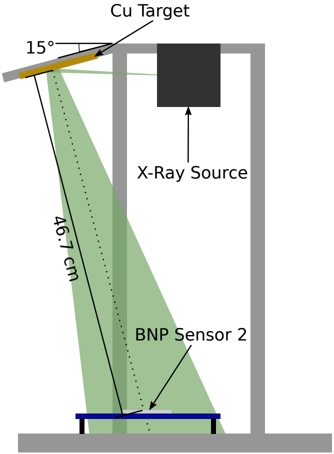


Is the bonding interface transparent to signals from X-Ray absorption?

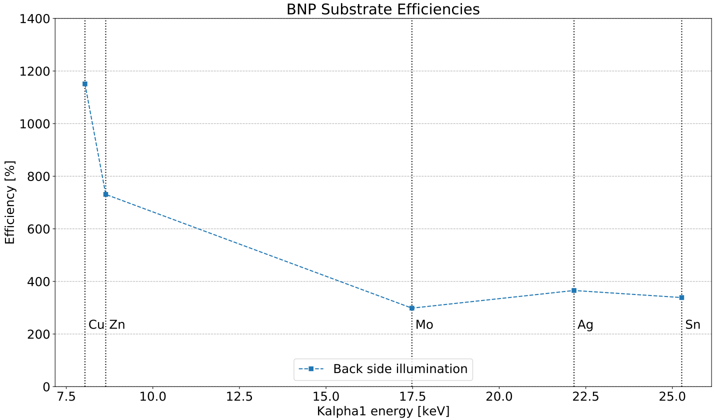
Efficiency Measurement Test Setup

Measurements carried out with fluorescent X-Ray beams.



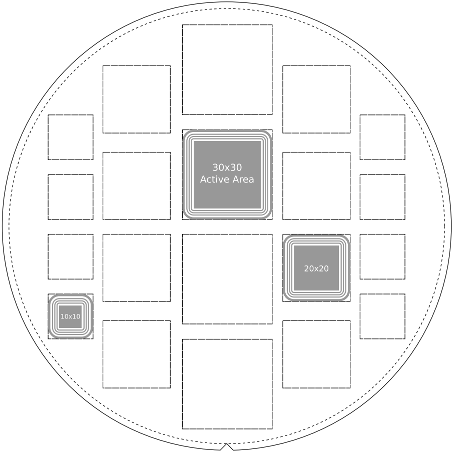


Substrate Efficiency Results



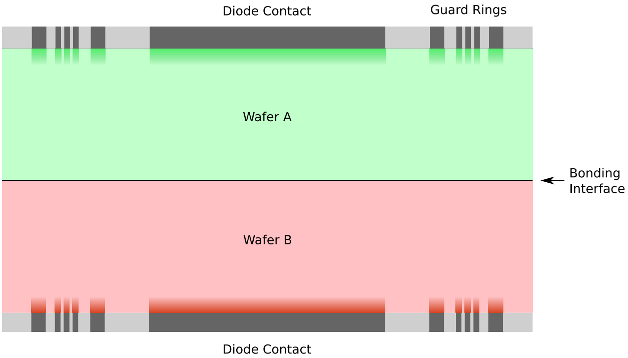
Higher than 100% substrate efficiency indicates at least partial transparency of the bonding interface!

Test Diodes Wafer Layout



- The exact layout of the test diode structures is not yet fixed
- Processing will be carried out at the joint IBM / ETHZ clean room at the *Binnig and Rohrer Nanotechnology Center*.

Cross Section of a Bonded Test Diode



🟩 N-Type Wafer 🟩 N-Type Implant 🟥 P-Type Wafer 🟥 P-Type Implant

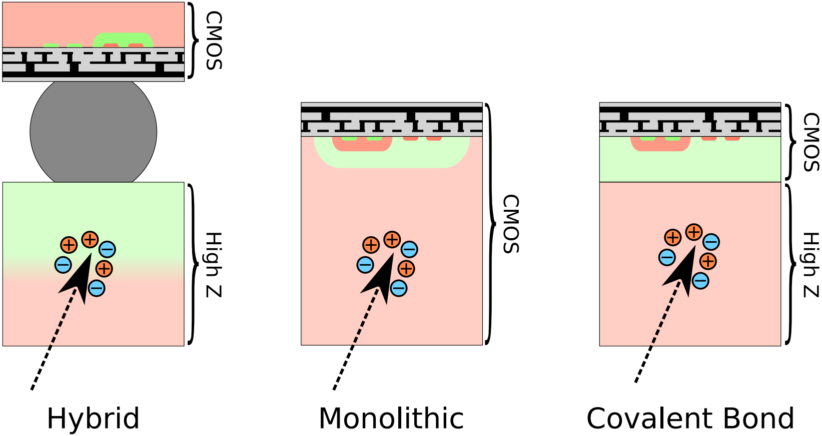
⬛ Metal (Al) ⬜ Oxide (SiO_2)

Measurement Plans

Measurements will go hand in hand with equivalent TCAD simulations

- Electrical measurements
  - I/V
  - C/V
  - Temperature dependent leakage current
- Transient current technique (TCT)
- X-Ray measurements
  - Signal shape analysis
  - Photon detection efficiency
  - Energy resolution

Recap



🟩 N Doped 🟥 P Doped ■ Bump Bond ▨ Metal Layers

Design Comparison

Hybrid

+ Free choice of absorber

- High cost and low yield due to bump bonding

- Pixel pitch limited by the bump bonds

Monolithic

+ Easier and cheaper to produce

+ High yield due to proven CMOS technology

- Limited to silicon absorbers

Bonded

+ Free choice of absorber

+ High yield due to bonding on a wafer level

- Influence of the interface

- Unproven technology

Conclusions

- Wafer-wafer bonding eliminates the need for bump bonding when building a semiconductor detector with a **non-silicon absorber**.
- The bonding process is fully **CMOS compatible**.
- **Initial results** with a commercial prototype are **promising**, but no definite conclusion is possible due to the complexity of the system.
- We are working on **characterizing the electrical properties** of the wafer bond for applications involving **particle detectors**.
- This technology could be complementary to **monolithic tracker detectors**.

Thank you for your attention!

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References I

[1] R. Morisaki, Y. Hirai, C. Oka, M. Mizoshiri, T. Yamazaki, J. Sakurai, T. Hirai, T. Takahashi, H. Tsuji, and S. Hata, “Development of a fast atom beam gun for surface-activated bonding,” *Precision Engineering*, vol. 62, pp. 106–112, Mar. 2020. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0141635919307640 (Accessed 2020-01-09).

[2] T. Suga, M. Howlader, T. Itoh, C. Inaka, Y. Arai, and A. Yamauchi, “A new wafer-bonder of ultra-high precision using surface activated bonding (SAB) concept,” in *2001 Proceedings. 51st Electronic Components and Technology Conference (Cat. No.01CH37220)*, May 2001, pp. 1013–1018, iSSN: 0569-5503.

References II

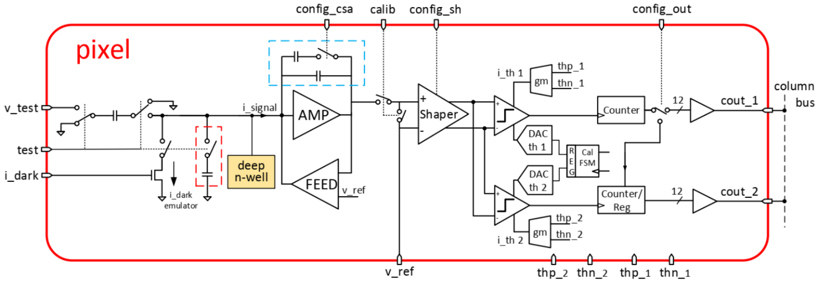
[3] EV Group, “EVG ComBond Brochure,” Jan. 2019. [Online]. Available: https://www.evgroup.com/fileadmin/media/products/bonding/Permanent_Bonding/combond/EVG_ComBond_Brochure_19_01.pdf (Accessed 2019-10-22).

[4] J. Neves, “Towards wafer-scale monolithic CMOS integrated pixel detectors for X-ray photon counting,” Vienna, Feb. 2019. [Online]. Available: https://indico.cern.ch/event/716539/contributions/3246033/ (Accessed 2019-07-05).


G-ray
BigNovipix Sensor
Rev.1 08.2018
G-ray
BigNovipix MainBoard
Rev.1 08.2018
J16
J10
RESET

Backup

Bignovipix Pixel Electronics



From [4]

Internal Photoelectric Effect