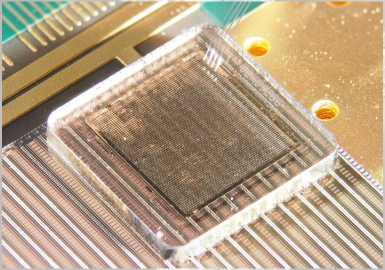
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



New Beam Test Results of 3D Pixel Detectors Constructed With Poly-Crystalline CVD Diamond

29th International Symposium on Lepton Photon Interactions at High Energies

Michael Reichmann

8 August 2019

Table of Contents

Section 1

Motivation

Diamond as Detector Material

- innermost tracking layers $\rightarrow$ highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- current detectors is designed to survive $\sim$12 month in High-Luminosity LHC
- $\rightarrow$ **R&D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material

- innermost tracking layers → highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- current detectors is designed to survive ∼12 month in High-Luminosity LHC
- → **R&D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- properties
  - radiation tolerant
  - isolating material
  - high charge carrier mobility
  - **smaller signal than in silicon with same thickness (large bandgap)**
  - **after $1 \cdot 10^{16}\,\mathrm{n/cm^2}$ the mean drift path in diamond larger than in silicon**

Diamond as Detector Material

- innermost tracking layers → highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- current detectors is designed to survive ∼12 month in High-Luminosity LHC
- → **R&D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- properties
  - radiation tolerant
  - isolating material
  - high charge carrier mobility
  - **smaller signal than in silicon with same thickness (large bandgap)**
  - **after $1 \cdot 10^{16}\,\mathrm{n/cm^2}$ the mean drift path in diamond larger than in silicon**

Work of RD42:

- investigate signals and radiation tolerance in various detector designs:
  - Pad Detectors → whole diamond as single cell readout
  - Pixel Detectors → diamond sensor on pixel readout chip
  - 3D Pixel Detectors → 3D diamond detector on pixel readout chip

Diamond as Detector Material

- innermost tracking layers $\rightarrow$ highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- current detectors is designed to survive $\sim$12 month in High-Luminosity LHC
- $\rightarrow$ **R&D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- properties
  - radiation tolerant
  - isolating material
  - high charge carrier mobility
  - **smaller signal than in silicon with same thickness (large bandgap)**
  - **after $1 \cdot 10^{16}\,\mathrm{n/cm^2}$ the mean drift path in diamond larger than in silicon**

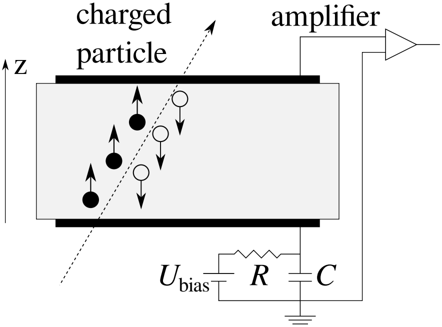
Work of RD42:

- investigate signals and radiation tolerance in various detector designs:
  - Pad Detectors
  - Pixel Detectors
  - **3D Pixel Detectors** $\rightarrow$ this talk

Section 2

3D Diamond Detector

Diamond as Particle Detector

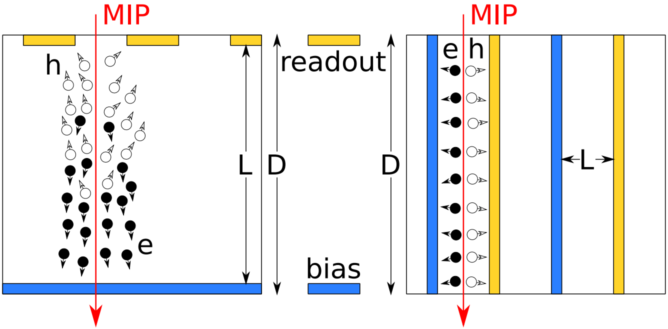


(a) Detector Schematics

(b) 15 cm ⌀ pCVD Diamond Wafer

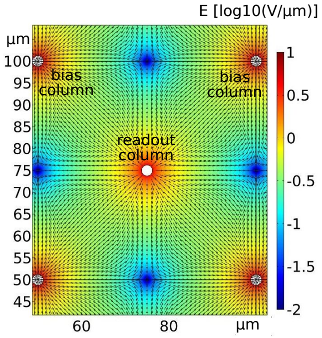
- detectors function as ionisation chambers
- metallisation on both sides
- poly-crystals produced in large wafers

Working Principle



- after large radiation fluence all detectors become trap limited
- 3D = bias and readout electrode inside detector material
- same thickness D → same amount of induced charge → shorter drift distance L
- **increase collected charge in detectors with limited mean drift path (Schubweg)**

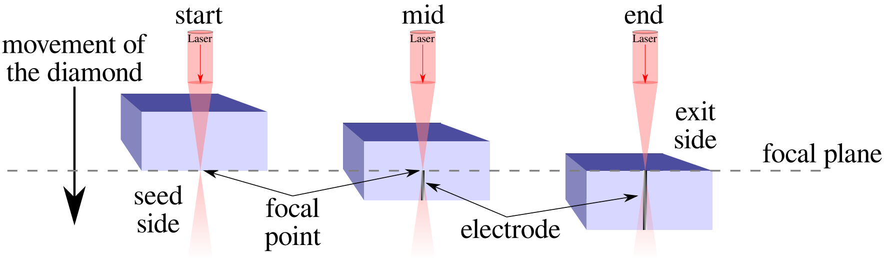
Electric Field Simulation



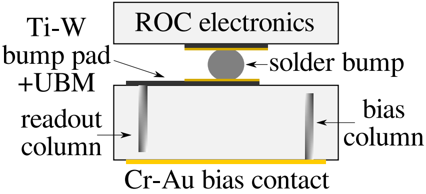
- simulation with 30 V bias voltage and periodic boundary conditions
- electric field ∼1 V/µm over a large area in the cell
- low field region in between the electrodes

Laser drilling

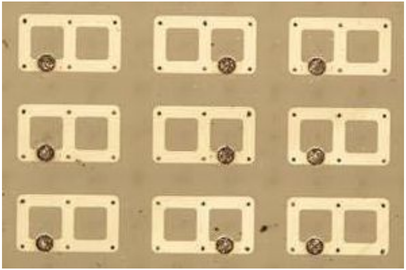
- "drilling" columns using 800 nm fs-LASER (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of Spatial Light Modulation (SLM) to correct for vertical aberration
- initial column yield $\sim$90 % $\rightarrow$ now $\geq$99 %
- initial column diameter 6 $\sim$ 10 μm $\rightarrow$ now 2.6 μm



Bump Bonding



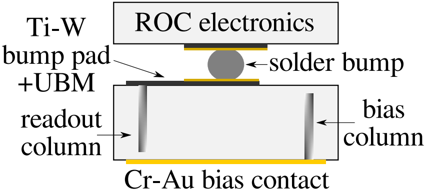
(a) Bump bond schematics



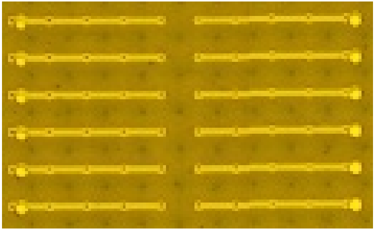
(b) 3×2 bump pads

- connection to bias and readout with surface metallisation
- ganging of cells to match pixel pitch of readout-chip (ROC)
- small gap ($\sim$15 µm) to the surface to avoid a high voltage break-through

Bump Bonding



(a) Bump bond schematics



(b) 1×5 bump pads

- connection to bias and readout with surface metallisation
- ganging of cells to match pixel pitch of readout-chip (ROC)
- small gap ($\sim$15 µm) to the surface to avoid a high voltage break-through

Progress in Diamond Detectors

3D Detectors - History in Diamonds:

- proved that 3D works in pCVD diamond
- scale up the number of columns per detector: $\mathcal{O}(100) \rightarrow \mathcal{O}(1000)$ (x40)
- reducing the cell size: $150\,\mu m \times 150\,\mu m \rightarrow 50\,\mu m \times 50\,\mu m \rightarrow 25\,\mu m \times 25\,\mu m$ (soon)
- reducing the diameter of the columns: $6 \sim 10\,\mu m \rightarrow 2.6\,\mu m \rightarrow 1 \sim 2\,\mu m$ (soon)
- $\rightarrow$ increasing column yield: $\sim 90\,\% \rightarrow \geq 99\,\%$
- recently tested first irradiated $50\,\mu m \times 50\,\mu m$ 3D detector $(3.5 \cdot 10^{15}\,n/cm^2)$

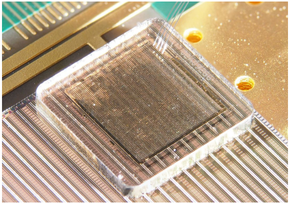
3D Pixel Detectors:

- visible improvements with each step reducing the cell size
- all worked as expected (to first order)

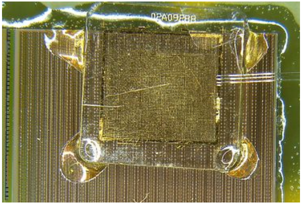
Section 3

Results

Detectors



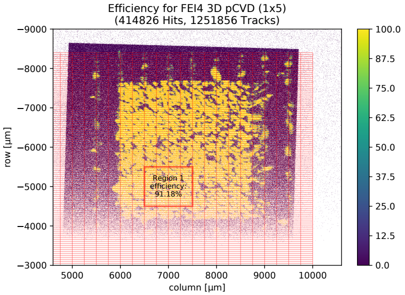
(a) II6-B5



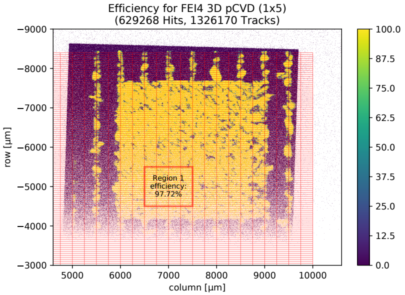
(b) II6-B6

	II6-B5	II6-B6
readout chip (ROC)	FEI4-b	PSI46digv2.1respin
pixel pitch	50 μm × 250 μm	150 μm × 100 μm
3D cell size	50 μm × 50 μm	50 μm × 50 μm
ganging	1 × 5	3 × 2
size	4.90 mm × 4.94 mm	4.85 mm × 4.90 mm
thickness	510 μm	?
50 pixels × 50 pixels	53 × 67	67 × 53
3D columns	7223	7223
column diameter	2.6 μm	2.6 μm
active area	3.2 mm × 3.5 mm	3.45 mm × 3.19 mm
bump bonding	tin silver (IFAE)	indium (Princeton)

II6-B5 - Efficiencies @ CERN



(a) High threshold (1500 e)



(b) Low threshold (1000 e)

- spatial resolution of ~3 μm
- two different tunings of the FEI4 chip
- efficiency with low threshold significantly higher: 97.7 %
- inefficiencies most likely due to bump bonding issues

Time Over Threshold

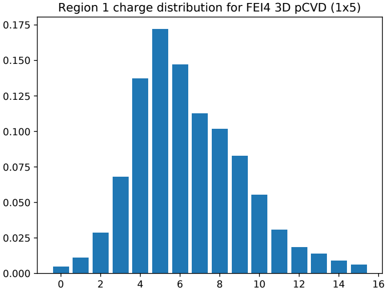
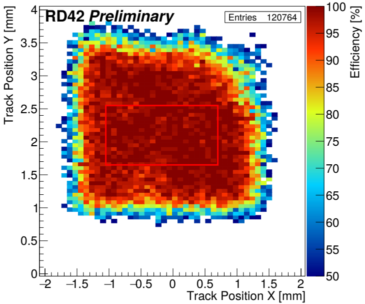


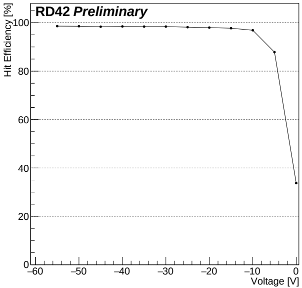
Figure: Time over threshold

- 5 tot $\approx$ 11 000 e
- MPV of the ToT distribution: 5 $\rightarrow$ 11 000 e
- roughly 80 % the induced charge was collected

II6-B6 - Efficiencies @ PSI



(a) Efficiency Map



(b) Efficiency vs. voltage.

- beam test right after the first bump bonding (top right corner badly bonded)
- spatial resolution of $\mathcal{O}\,(100\,\mu\mathrm{m})$
- efficiency in red fiducial area: 99.2 % ($\rightarrow$ columns (0.4 %) & low field regions)
- already fully efficient at 30 V
- ROC stopped working after this beam test

Pulse Height @ PSI

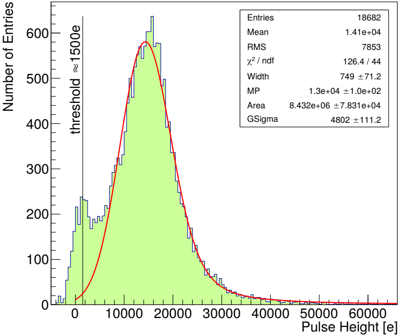


Figure: Pulse height distribution.

- trimmed threshold: ∼1500 e
- Langau MPV: 13 500 e
- unreal distribution below threshold most likely due to data transmission problems

Efficiencies @ CERN

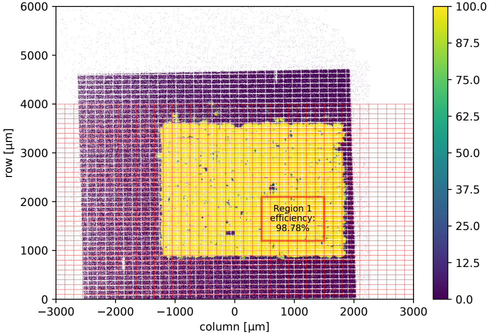


Figure: Efficiency at threshold of ∼3500 e

- high resolution measurement at CERN
- find non-working/non-connected cells
- sensor twice re-bump-bonded with the same indium (no reprocessing)
  - no removal of old bumps, no change of surface metallisation
- similar efficiency: 99.1 %

Pulse Height @ CERN

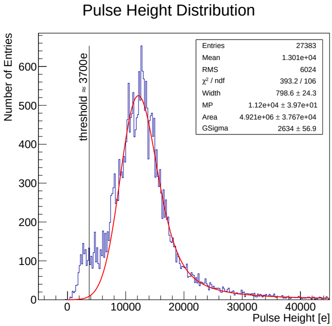


Figure: Pulse height distribution.

- trimmed threshold: ∼3700 e
- Langau MPV: 11 000 e
- pulse height very similar to FEIV-b result at CERN
- beam particles at CERN have less energy loss → lower MPV
- unreal distribution below threshold most likely due to data transmission problems

Section 4

Conclusion

Conclusion

- strongly improved fabrication of 3D diamonds
  - 40 times more cells
  - smaller cell size down to 50 µm × 50 µm
  - thinner columns down to 2 µm
- 3D Detectors work well in pCVD diamond
- 99.2 % efficiency in 3 × 2 ganged device
  - inefficiencies most likely due to low field regions and columns itself
- 97.7 % efficiency in 1 × 5 ganged device
  - most likely bump bonding issues
- consistent charge measurements for all devices: ∼11 000 e @ CERN SPS
- nearly full charge collection

Section 5

Outlook

Outlook

- analyse $3.5 \cdot 10^{15}\,\mathrm{n/cm^2}$ irradiated $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ detectors
- test both $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ and $25\,\mu\mathrm{m} \times 25\,\mu\mathrm{m}$ pixel detectors
- reduce column diameter to $1 \sim 2\,\mu\mathrm{m}$
- build pixel device on newest RD53 chip ($50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ pixel pitch)
- continue scale up by 10x

Del Fin