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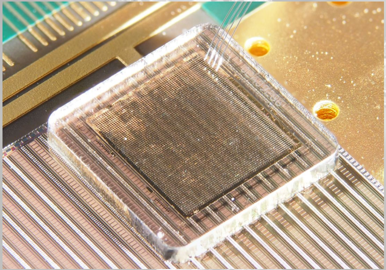

New Beam Test Results of 3D Pixel Detectors Constructed With Poly-Crystalline CVD Diamond

29th International Symposium on Lepton Photon Interactions at High Energies, Toronto, ON, Canada

Michael Reichmann on behalf of the RD42 Collaboration

8 August 2019

Section 1

Motivation

Diamond as Detector Material

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

Diamond as Detector Material

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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**

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Work of RD42:

- investigate signals and radiation tolerance in various detector designs:
  - Pad Detectors → whole diamond as single cell readout (Lukas' Talk)
  - 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 would survive $\sim$12 month in High-Luminosity LHC
- $\rightarrow$ **R&D for more radiation tolerant detector designs and/or materials**

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Work of RD42:

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

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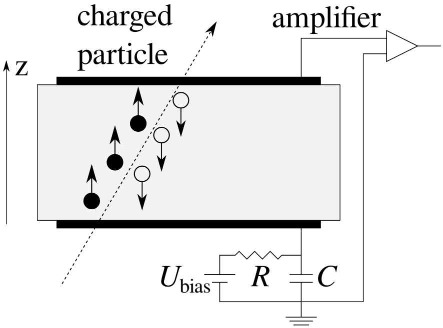
Section 2

3D Diamond Detector

Diamond as Particle Detector

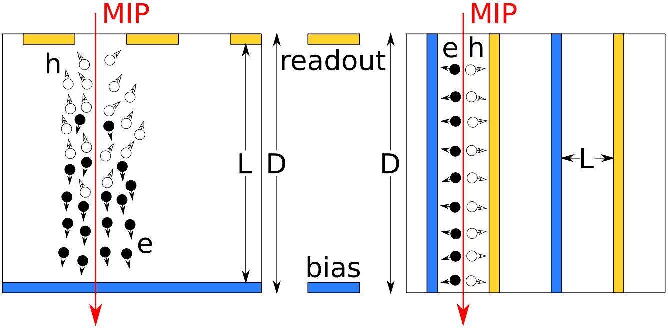


(a) Detector Schematics

(b) 15 cm ⌀ pCVD Diamond Wafer

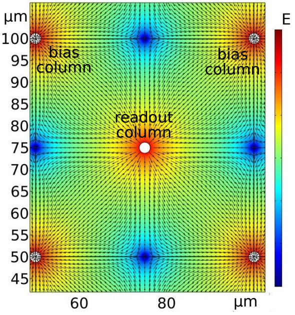
- detectors function as ionisation chambers
- metallisation on both sides
- poly-crystals produced in large wafers

Working Principle



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

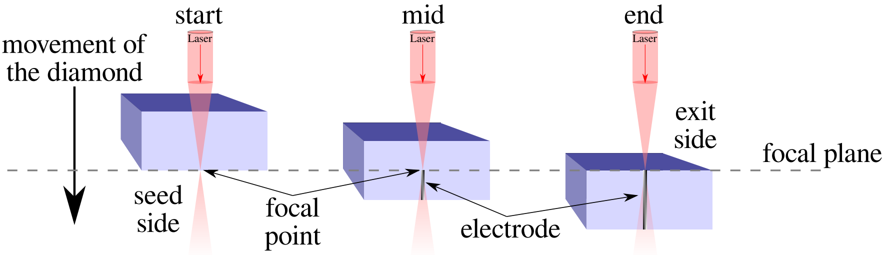
Electric Field Simulation



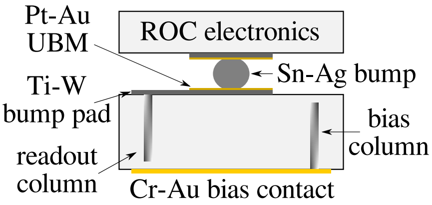
- simulation with 30 V bias voltage and periodic boundary conditions
- electric field ∼1 V/µm over a large area in the cell
- low field region in between the electrodes

Laser drilling

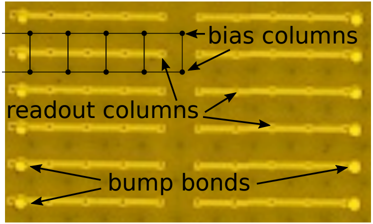
- "drilling" columns using 800 nm fs-LASER (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of Spatial Light Modulator (SLM) to correct for spherical aberration
- initial column yield $\sim$90 % $\rightarrow$ now **$\gtrsim$99.8 %**
- initial column diameter 6 $\sim$ 10 µm $\rightarrow$ now **2.6 µm**



Bump Bonding



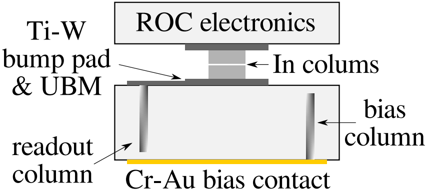
(a) Bump bond schematics



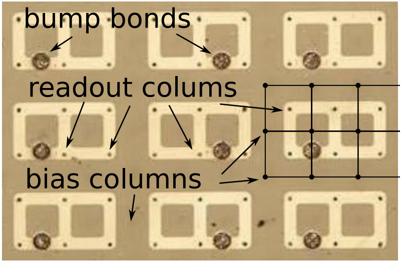
(b) 5 × 1 bump pads

- connection to bias and readout with surface metallisation
- ganging of cells to match pixel pitch of readout-chip (ROC)
- small gap (∼15 µm) to the surface

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 (∼15 μm) to the surface

Progress in Diamond Detectors

3D Detectors - History in Diamonds:

- proved that 3D works in pCVD diamond
- scale up the number of 3D-cells per detector: $\mathcal{O}(100) \rightarrow \boldsymbol{\mathcal{O}(4000)}$ ($\times 40$)
- reducing the cell size: $150\,\mu\text{m} \times 150\,\mu\text{m} \rightarrow \mathbf{50\,\mu m \times 50\,\mu m} \rightarrow 25\,\mu\text{m} \times 25\,\mu\text{m}$ (soon)
- reducing the diameter of the columns: $6 \sim 10\,\mu\text{m} \rightarrow \mathbf{2.6\,\mu m} \rightarrow 1 \sim 2\,\mu\text{m}$ (soon)
- $\rightarrow$ increasing column yield: $\sim 90\,\%$ $\rightarrow$ $\gtrsim \mathbf{99.8\,\%}$
- recent beam test of irradiated $50\,\mu\text{m} \times 50\,\mu\text{m}$ 3D detector ($3.5 \cdot 10^{15}\,\text{n/cm}^2$)

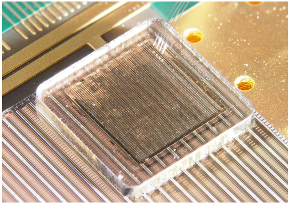
3D Pixel Detectors:

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

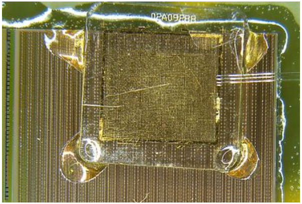
Section 3

Results

Detectors



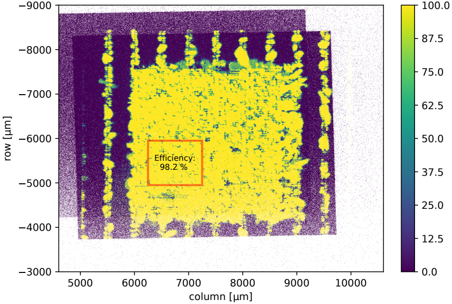
(a) B5



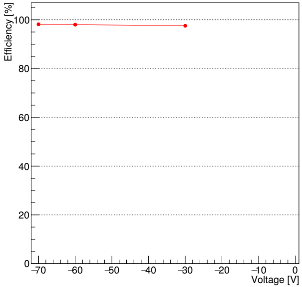
(b) B6

	B5	**B6**
readout chip (ROC)	FE-I4B	PSI46digv2.1respin
pixel pitch	250 µm × 50 µm	150 µm × 100 µm
3D cell size	50 µm × 50 µm	50 µm × 50 µm
ganging	5 × 1	3 × 2
size	4.90 mm × 4.94 mm	4.85 mm × 4.90 mm
thickness	510 µm	500 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)

B5 (5 × 1) - Efficiency @ CERN



(a) Efficiency map @ −70 V



(b) Efficiency vs. bias voltage.

- telescope tracking resolution at DUT: ∼3 μm
- threshold of the chip: ∼1000 e
- efficiency in red fiducial area 98.2 %
- inefficiencies most likely due to processing issues

Time Over Threshold

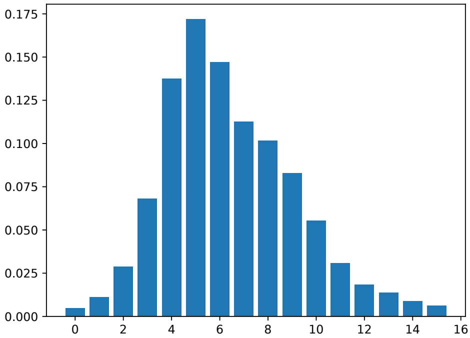
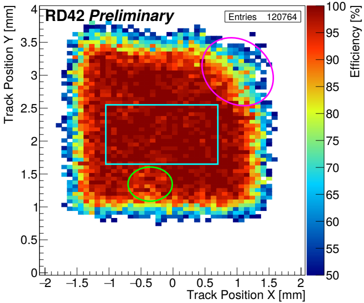


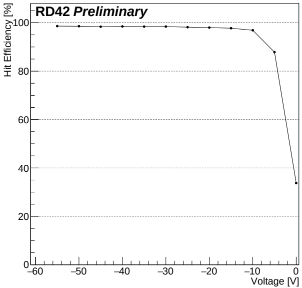
Figure: Time over threshold distribution.

- looks very similar to silicon distribution
- 5 tot $\approx$ 11 000 e
- mean of the ToT distribution: 6.7 $\rightarrow$ $\sim$14 500 e
- $\sim$80 % the induced charge was collected

B6 (3 × 2) - Efficiencies @ PSI



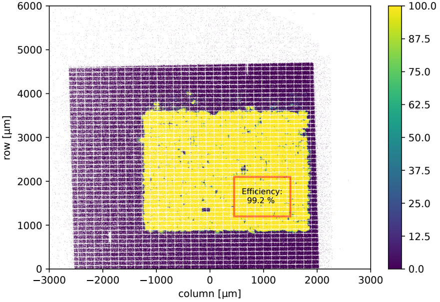
(a) Efficiency Map



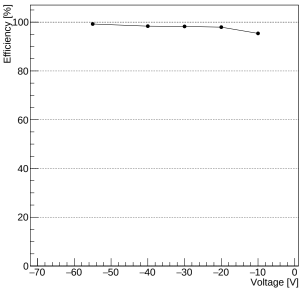
(b) Efficiency vs. voltage.

- telescope tracking resolution at DUT: $\mathcal{O}\,(100\,\mu\mathrm{m})$
- magenta area → bump bonding problems, green area → void in the diamond
- efficiency in blue box: 99.2 % (→ 99.6 % expected due to columns)
- efficiency already plateaus at 30 V
- ROC stopped working after this beam test

Efficiencies @ CERN



(a) Efficiency at threshold of ∼3500 e.



(b) Efficiency vs. bias voltage.

- high resolution measurement at CERN
- locate 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
- same efficiency: 99.2 %

Pulse Height @ CERN

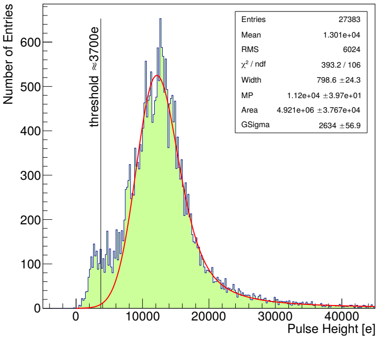


Figure: Pulse height distribution.

- threshold of the chip: ∼3700 e
- mean from MC of Langau fit: ∼14 500 e
- pulse height very similar to 5 × 1 result at CERN
- distribution below threshold not understood (maybe local data transmission issues)

Section 4

Conclusion

Conclusion

- 3D Detectors work well in pCVD diamond
- strongly improved fabrication of 3D diamond detectors
  - $40\times$ more cells
  - smaller cell size down to $50\,\mu m \times 50\,\mu m$
  - thinner columns down to $2.6\,\mu m$
- general reasons for inefficiencies:
  - less charge created in the volume of the electrodes (0.4 % for shown devices)
  - missing/broken columns (0.2 % for the full device)
  - region with low electric field $\rightarrow$ need precise simulations
- $(99.2 \pm 0.3)\,\%$ efficiency in 3×2 ganged device
- $(98.2 \pm 0.2)\,\%$ efficiency in 5×1 ganged device
  - discrepancy most likely due to different processing and bump bonding
- consistent mean charge measurements for all devices: $\sim$14 500 e @ CERN SPS
  - working on systematic effects
- 3D has largest charge collection of all pCVD diamond detectors
  - work towards quantifying the charge collection in both non- and irradiated devices

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 $10\,\times$

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