

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

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Michael Reichmann on behalf of the RD42 Collaboration

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Section 1

Motivation

Diamond as Detector Material

- innermost tracking layers \rightarrow highest radiation damage \mathcal{O} (GHz/cm²)
- current detectors would survive ~ 12 month in High-Luminosity LHC
- \rightarrow **R&D for more radiation tolerant detector designs and/or materials**

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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 $1 \cdot 10^{16}$ n/cm² 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 \rightarrow whole diamond as single cell readout (Lukas' Talk)
 - ▶ Pixel Detectors \rightarrow diamond sensor on pixel readout chip
 - ▶ 3D Pixel Detectors \rightarrow 3D diamond detector on pixel readout chip

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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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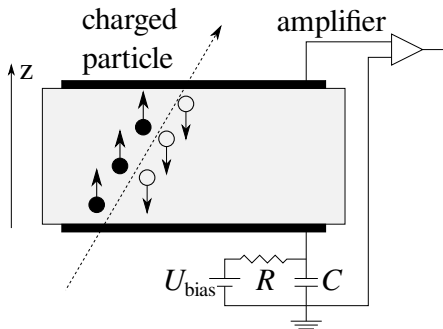
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30 institutes

Section 2

3D Diamond Detector

Diamond as Particle Detector



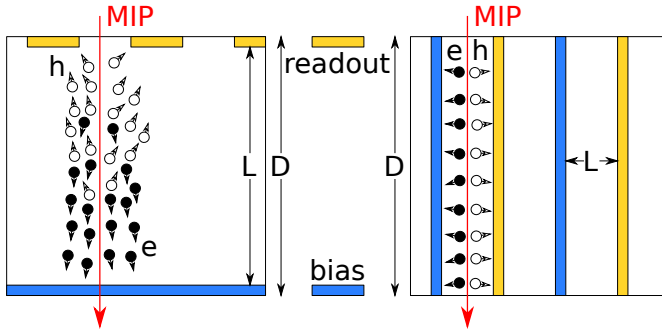
(a) Detector Schematics



(b) 15 cm \varnothing pCVD Diamond Wafer

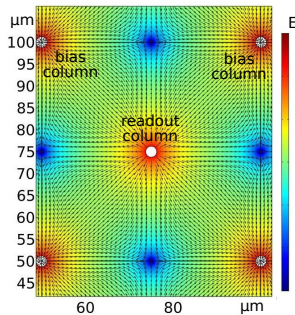
- detectors function as ionisation chambers
- metallisation on both sides
- poly-crystals produced in large wafers

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**

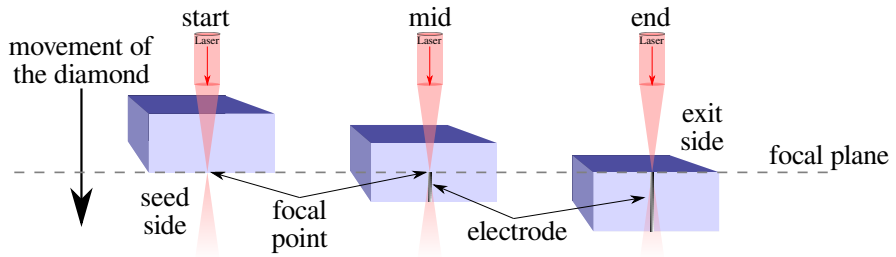
Electric Field Simulation



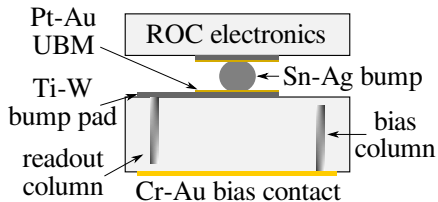
- simulation with 30 V bias voltage and periodic boundary conditions
- electric field $\sim 1 \text{ V}/\mu\text{m}$ over a large area in the cell
- low field region in between the electrodes

Laser drilling

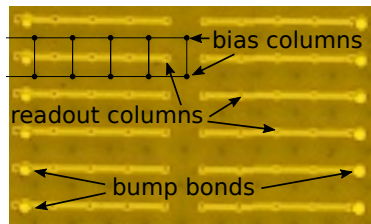
- “drilling” columns using 800 nm fs-LASER (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of Spatial Light Modulator (SLM) to correct for spherical aberration
- initial column yield $\sim 90\%$ \rightarrow now $\gtrsim 99.8\%$
- initial column diameter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



Bump Bonding



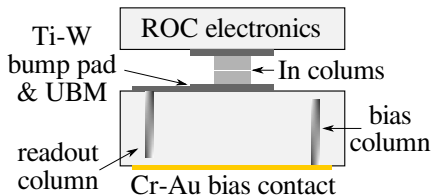
(a) Bump bond schematics



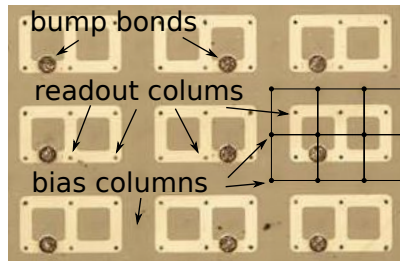
(b) 5×1 bump pads

- connection to bias and readout with surface metallisation
- ganging of cells to match pixel pitch of readout-chip (ROC)
- small gap ($\sim 15 \mu\text{m}$) 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 ($\sim 15 \mu\text{m}$) to the surface

Progress in Diamond Detectors

3D Detectors - History in Diamonds:

- proved that 3D works in pCVD diamond
- scale up the number of columns per detector: $\mathcal{O}(100) \rightarrow \mathcal{O}(1000) (\times 40)$
- reducing the cell size: $150\text{ }\mu\text{m} \times 150\text{ }\mu\text{m} \rightarrow 50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m} \rightarrow 25\text{ }\mu\text{m} \times 25\text{ }\mu\text{m}$ (soon)
- reducing the diameter of the columns: $6 \sim 10\text{ }\mu\text{m} \rightarrow 2.6\text{ }\mu\text{m} \rightarrow 1 \sim 2\text{ }\mu\text{m}$ (soon)
- \rightarrow increasing column yield: $\sim 90\% \rightarrow \gtrsim 99.8\%$
- recently tested first irradiated $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ 3D detector ($3.5 \cdot 10^{15}\text{ n/cm}^2$)

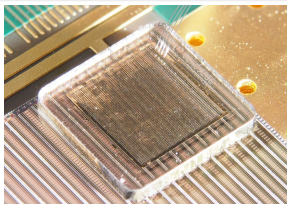
3D Pixel Detectors:

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

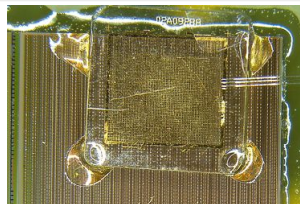
Section 3

Results

Detectors



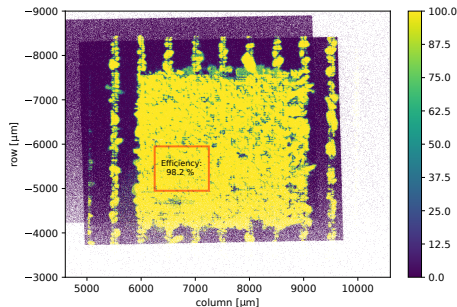
(a) B5



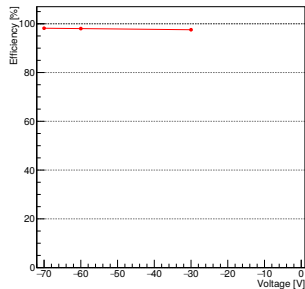
(b) B6

	B5	B6
readout chip (ROC)	FE-I4B	PSI46digv2.1respin
pixel pitch	$250\ \mu\text{m} \times 50\ \mu\text{m}$	$150\ \mu\text{m} \times 100\ \mu\text{m}$
3D cell size	$50\ \mu\text{m} \times 50\ \mu\text{m}$	$50\ \mu\text{m} \times 50\ \mu\text{m}$
ganging	5×1	3×2
size	$4.90\ \text{mm} \times 4.94\ \text{mm}$	$4.85\ \text{mm} \times 4.90\ \text{mm}$
thickness	$510\ \mu\text{m}$	$500\ \mu\text{m}$
50 pixels \times 50 pixels	53×67	67×53
3D columns	7223	7223
column diameter	$2.6\ \mu\text{m}$	$2.6\ \mu\text{m}$
active area	$3.2\ \text{mm} \times 3.5\ \text{mm}$	$3.45\ \text{mm} \times 3.19\ \text{mm}$
bump bonding	tin silver (IFAE)	indium (Princeton)

B5 (5 × 1) - Efficiency @ CERN



(a) Efficiency map @ -70 V



(b) Efficiency vs. bias voltage.

- spatial resolution of $\sim 3 \mu\text{m}$
- threshold of the chip: $\sim 1000 e$
- efficiency in red fiducial area 98.2 %
- inefficiencies most likely due to processing issues

Time Over Threshold

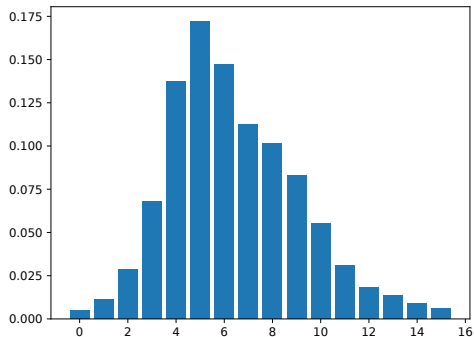
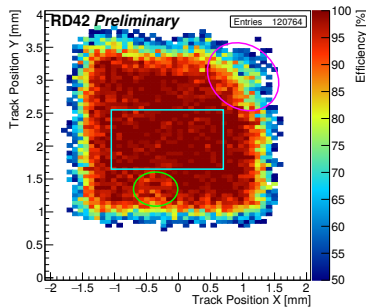


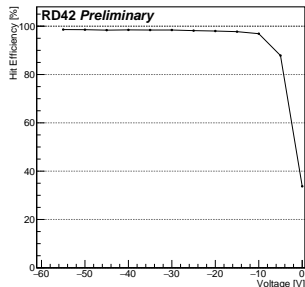
Figure: Time over threshold distribution.

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

B6 (3 × 2) - Efficiencies @ PSI



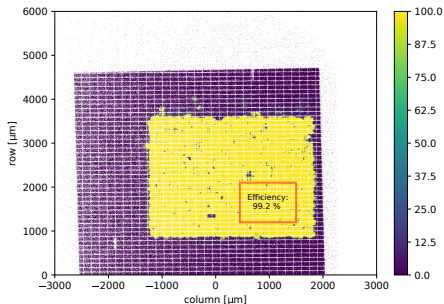
(a) Efficiency Map



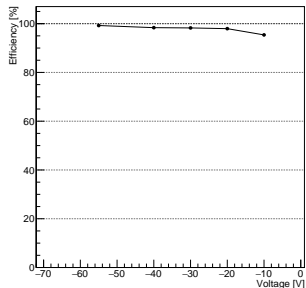
(b) Efficiency vs. voltage.

- spatial resolution of $\mathcal{O}(100\ \mu\text{m})$
- magenta area \rightarrow bump bonding problems, green area \rightarrow void in the diamond
- efficiency in blue box: 99.2 % (\rightarrow 99.6 % expected due to columns)
- already fully efficient 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

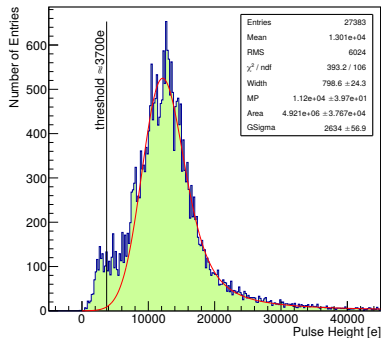


Figure: Pulse height distribution.

- threshold of the chip: ~ 3700 e
- mean from MC of Langau fit: ~ 14500 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 $50 \mu\text{m} \times 50 \mu\text{m}$
 - ▶ thinner columns down to $2.6 \mu\text{m}$
- 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: $\sim 14\,500\text{e}$ @ CERN SPS
 - ▶ work 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

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

DEL FIN

