

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

29th International Symposium on Lepton Photon Interactions at High Energies

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8 August 2019

- 1 Motivation
- 2 3D Diamond Detector
- 3 Results
- 4 Conclusion
- 5 Outlook

Section 1

Motivation

Diamond as Detector Material

- innermost tracking layers \rightarrow highest radiation damage \mathcal{O} (GHz/cm²)
- current detectors is designed to 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
 - ▶ Pixel Detectors \rightarrow diamond sensor on pixel readout chip
 - ▶ 3D Pixel Detectors \rightarrow 3D diamond detector on pixel readout chip

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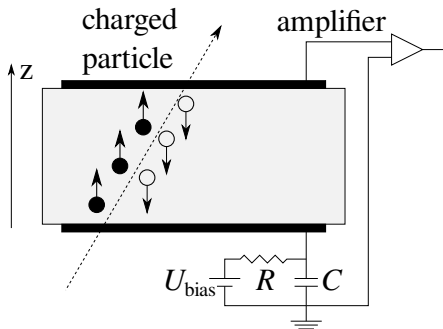
Work of RD42:

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

Section 2

3D Diamond Detector

Diamond as Particle Detector



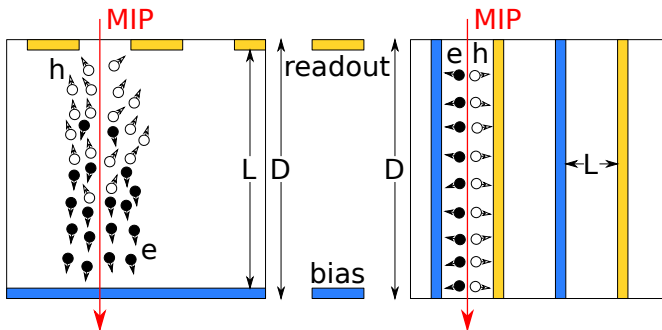
(a) Detector Schematics



(b) 15 cm \varnothing pCVD Diamond Wafer

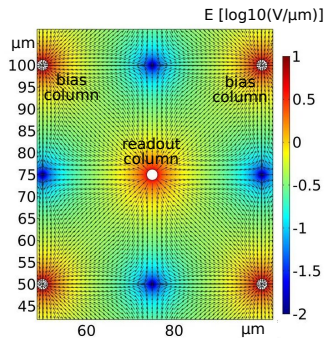
- detectors function as ionisation chambers
- metallisation on both sides
- poly-crystals produced in large wafers

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**

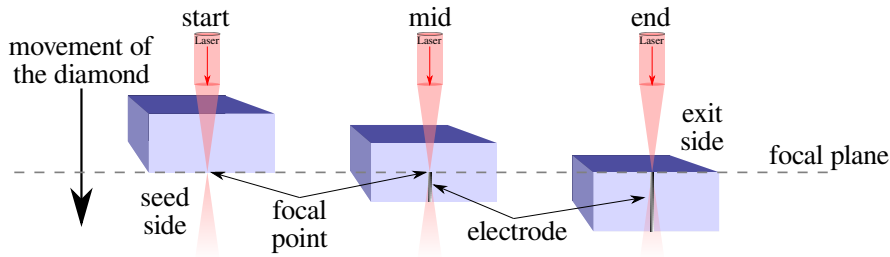
Electric Field Simulation



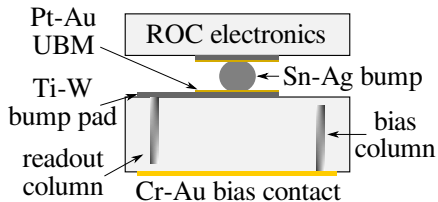
- simulation with 30 V bias voltage and periodic boundary conditions
- electric field $\sim 1 V/\mu m$ over a large area in the cell
- low field region in between the electrodes

Laser drilling

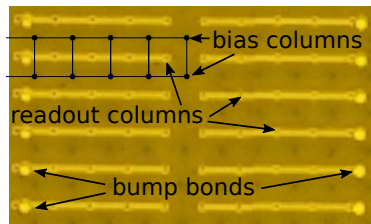
- “drilling” columns using 800 nm fs-LASER (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of Spatial Light Modulation (SLM) to correct for vertical aberration
- initial column yield $\sim 90\%$ \rightarrow now $\geq 99\%$
- initial column diameter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



Bump Bonding



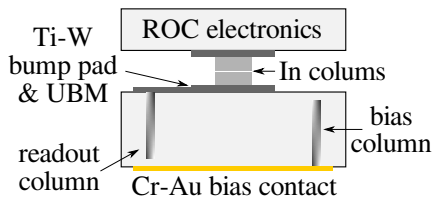
(a) Bump bond schematics



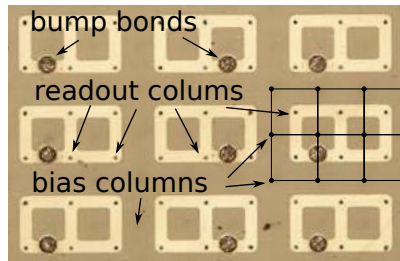
(b) 5×1 bump pads

- 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: $\mathcal{O}(100) \rightarrow \mathcal{O}(1000)$ (x40)
- 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: $\sim 90\% \rightarrow \geq 99.8\%$
- recently tested first irradiated $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ 3D detector ($3.5 \cdot 10^{15}\text{ n/cm}^2$)

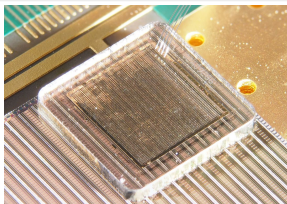
3D Pixel Detectors:

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

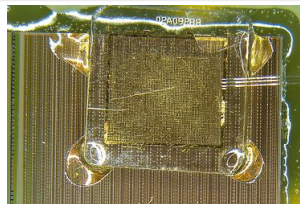
Section 3

Results

Detectors



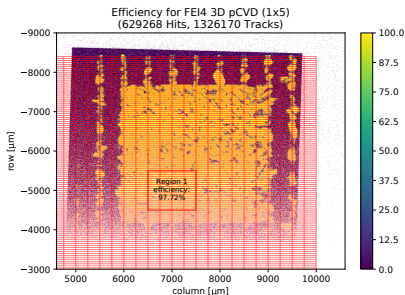
(a) B5



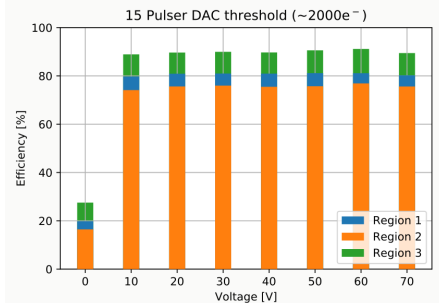
(b) B6

	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)

II6-B5 - Efficiencies @ CERN



(a) Efficiency map.



(b) Efficiency vs. bias voltage

- spatial resolution of $\sim 3\mu\text{m}$
- threshold of the chip: $\sim 1000e^-$
- efficiency in red fiducial area 97.7 %
- inefficiencies most likely due to bump bonding issues

Time Over Threshold

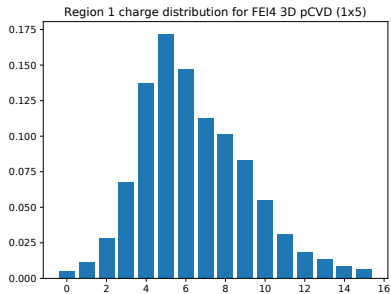
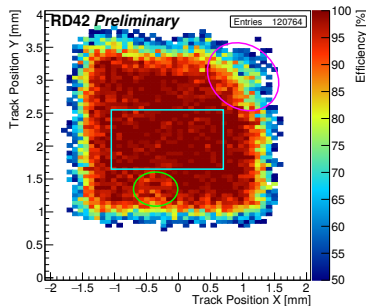


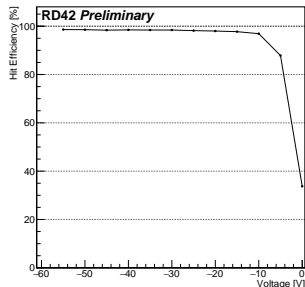
Figure: Time over threshold

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

I16-B6 - 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 0.4 % due to columns)
- already fully efficient at 30 V
- ROC stopped working after this beam test

Efficiencies @ CERN

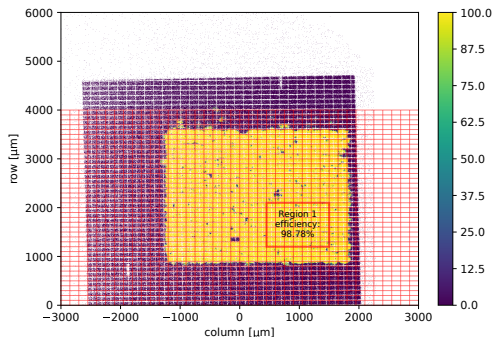


Figure: Efficiency at threshold of ~ 3500 e

- 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

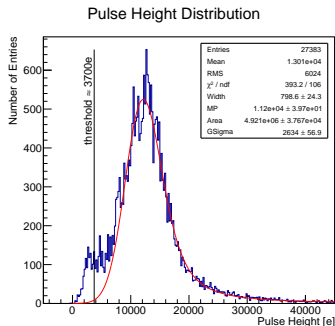


Figure: Pulse height distribution.

- threshold of the chip: ~ 3700 e
- Langau MPV: 11 000 e
- pulse height very similar to $5 \text{ r} \times 1$ result at CERN
- beam particles at CERN have less energy loss \rightarrow lower MPV
- also distribution below threshold

Section 4

Conclusion

Conclusion

- strongly improved fabrication of 3D diamonds
 - ▶ 40 times more cells
 - ▶ smaller cell size down to $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$
 - ▶ thinner columns down to $2\text{ }\mu\text{m}$
- 3D Detectors work well in pCVD diamond
- 99.2 % efficiency in 3×2 ganged device
 - ▶ inefficiencies due to the columns itself
- 97.7 % efficiency in 5×1 ganged device
 - ▶ most likely bump bonding issues
- consistent charge measurements for all devices: $\sim 11\,000\text{ e}$ @ CERN SPS
- nearly full charge collection

Section 5

Outlook

Outlook

- 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 10x

