

New Test Beam Results of 3D and Pad Detectors Constructed with Poly-Crystalline CVD Diamond

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Section 1

Motivation

Diamond as Detector Material

- innermost tracking layers \rightarrow highest radiation damage \mathcal{O} (GHz/cm²)
- current detectors is designed to survive \sim 12 month in High-Luminosity LHC
- \rightarrow CERN 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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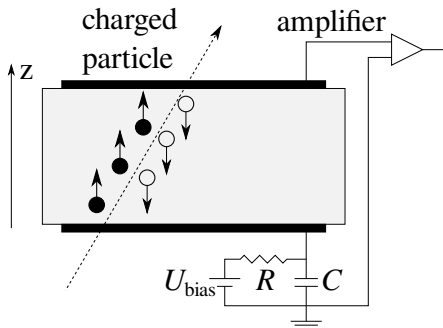
Work of RD42:

- investigate signals and radiation tolerance in various detector designs:
 - ▶ pad \rightarrow full diamond as single cell readout
 - ▶ pixel \rightarrow diamond sensors on state-of-the-art pixel chips
 - ▶ 3D pixel \rightarrow detector with design to reduce drift distance

Section 2

Introduction

Diamond as Particle Detector



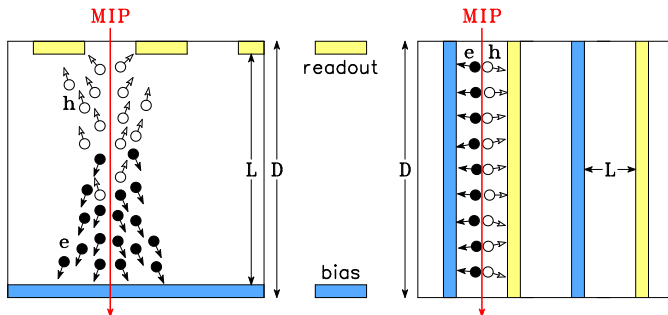
(a) Detector Schematics



(b) 15 cm pCVD Diamond Wafer

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

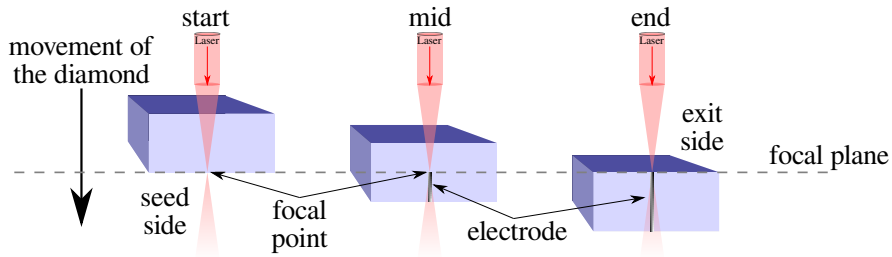
Working Principle



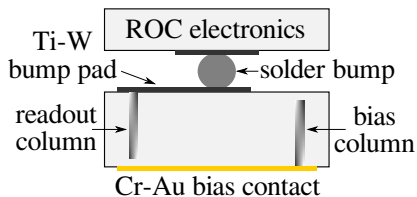
- after large radiation fluence all detectors become trap limited
- bias and readout electrode inside detector material
- same thickness $D \rightarrow$ same amount of induced charge \rightarrow shorter drift distance L
- **increase collected charge in detectors with limited mean drift path (Schubweg)**

Laser drilling

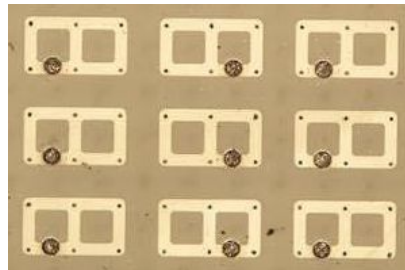
- “drilling” columns using 800 nm fs-LASER (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of Spatial Light Modulation (SLM) to correct for vertical aberration
- initial column yield $\sim 90\%$ \rightarrow now $\geq 99\%$
- initial column diameter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



Bump Bonding



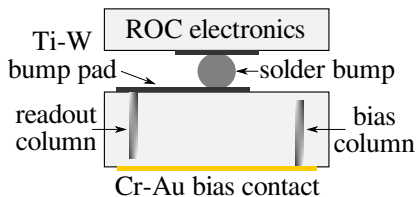
(a) Bump bond schematics



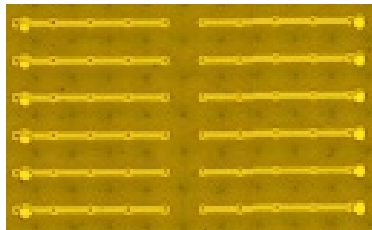
(b) 3×2 bump pads

- 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 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)
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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: $\sim 90\% \rightarrow \geq 99\%$
- 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)

Rate Studies in Pad Detectors:

- particle fluxes from 1 kHz/cm^2 up to 20 MHz/cm^2
- irradiations up to $4 \cdot 10^{15}\text{ n/cm}^2$

Section 3

3D Pixel Detectors

1 × 5 Ganging

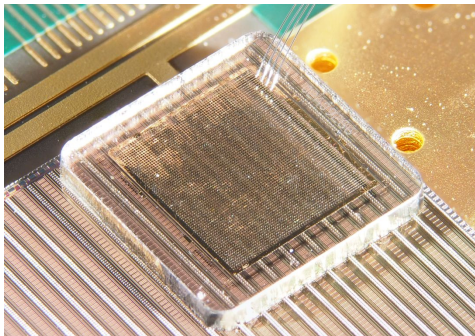
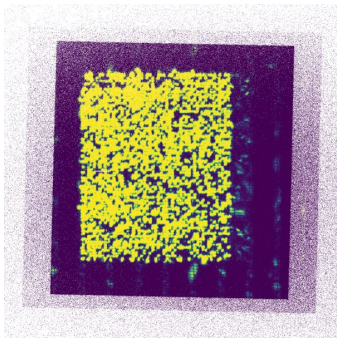


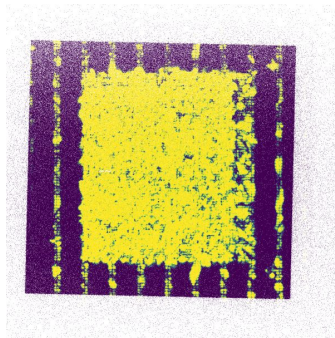
Figure: Final Detector

- readout chip (ROC): ATLAS FEI4
- Size: 5 mm × 5 mm
- active area 3 mm × 3 mm
- tin-silver bump bonding at IFAE (Barcelona)

Efficiencies



(a) High threshold



(b) Low threshold

- efficiencies

Time Over Threshold

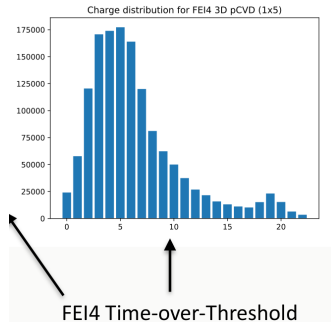


Figure: Time over threshold

- 5 tot $\approx 10\,000\text{ e}$
- mean of the ToT distribution: $6.53 \rightarrow 13\,000\text{ e}$
- 71 % of the charge collected

2 × 3 Ganging

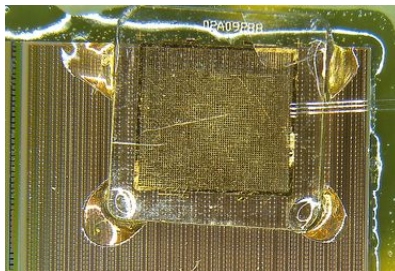
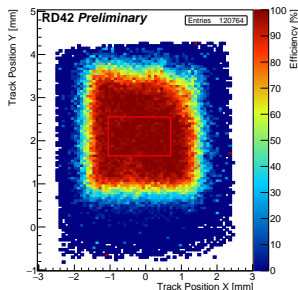


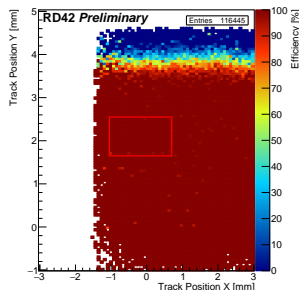
Figure: Final Detector

- readout chip (ROC): CMS PSI46digv2.1repspin
- Size: 5 mm × 5 mm
- active area 3.5 mm × 3.5 mm
- indium bump-bonding (Princeton)

Efficiencies - First PSI Beam Test



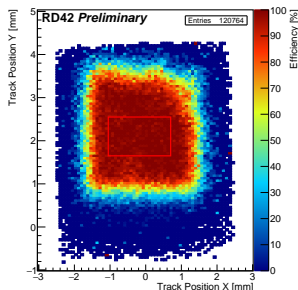
(a) Efficiency Map Diamond



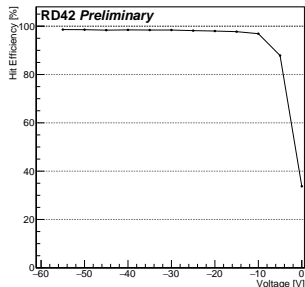
(b) Efficiency Map Silicon

- beam test right after the first bump bonding (top right corner badly bonded)
- spatial resolution of $\mathcal{O}(100\ \mu\text{m})$
- efficiency in red fiducial area: Diamond: 99.1 %, Silicon: 99.9 %

Efficiencies - First PSI Beam Test



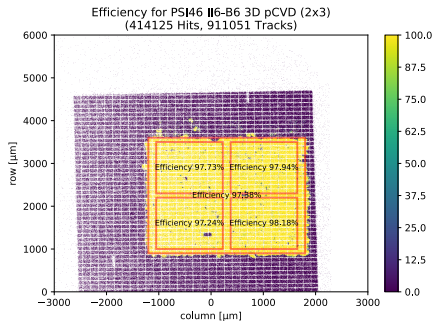
(a) Efficiency Map



(b) Efficiency vs. voltage

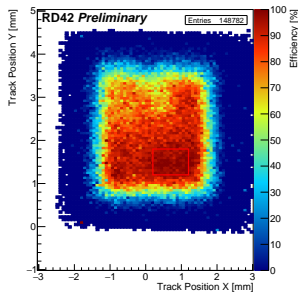
- beam test right after the first bump bonding (top right corner badly bonded)
- spatial resolution of $\mathcal{O}(100\ \mu\text{m})$
- effective efficiency (relative to silicon) in red fiducial area: 99.2 %
- already fully efficient at 30 V
- ROC stopped working after this beam test

Efficiencies - CERN Beam Test

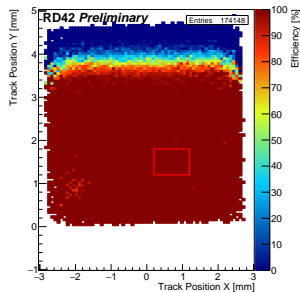


- high resolution measurement at CERN
- sensor twice re-bump-bonded with the same indium (no reprocessing)
 - ▶ no removal of old bumps, no change of surface metallisation
- non working columns not accounted in efficiency

Efficiencies - Second PSI Beam Test



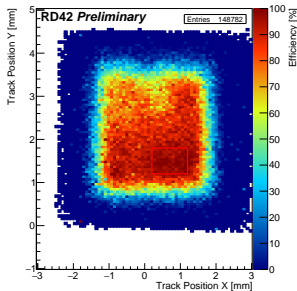
(a) Efficiency Map Diamond



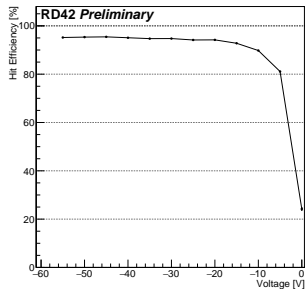
(b) Efficiency Map Silicon

- sensor twice re-bump-bonded with the same indium (no reprocessing)
- efficiency in red fiducial area: Diamond: 97.3 %, Silicon: 100.0 %

Efficiencies - Second PSI Beam Test



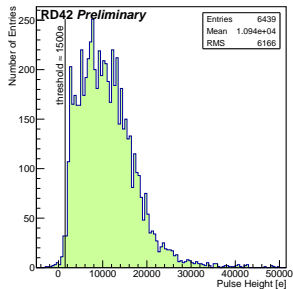
(a) Efficiency Map



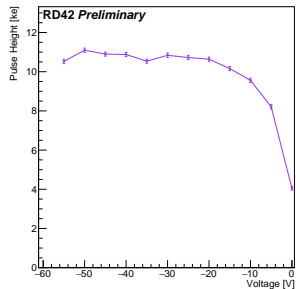
(b) Efficiency vs. voltage

- sensor twice re-bump-bonded with the same indium (no reprocessing)
- effective efficiency in red fiducial area: 97.3 %
- already fully efficient at 30 V
- only very small area working well → many bump bond problems

Pulse Height - Second Beam Test



(a) Signal Distribution



(b) Pulse height vs. voltage

- wrong pulse height calibration in first beam test
- full charge collection also at 30 V
- mean pulse height: 11 000 e
- low pulse height not understood

Section 4

Pad Detectors (Rate Studies)

Leakage Currents

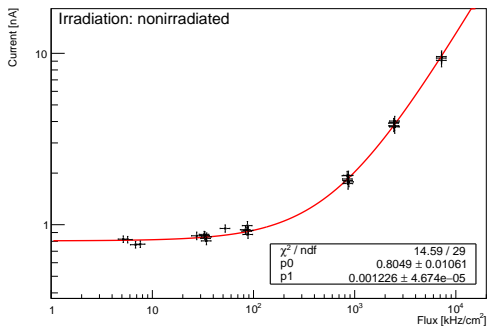
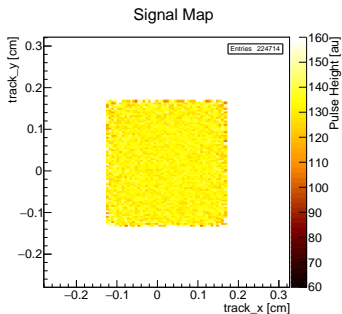


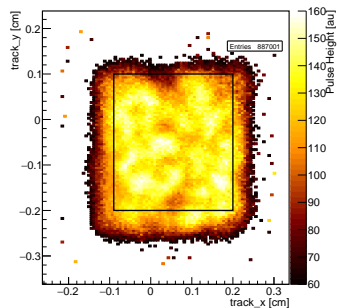
Figure: Leakage Current of a non-irradiated pCVD diamond

- very low base leakage current (no beam) of $\mathcal{O}(1 \text{ nA})$
- leakage current of most of the diamonds linear in flux
- basis of most diamond beam monitors at CERN

Signal Maps



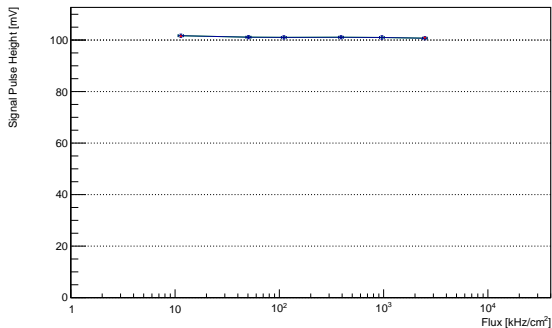
(a) scCVD (6 dB attenuation)



(b) pCVD

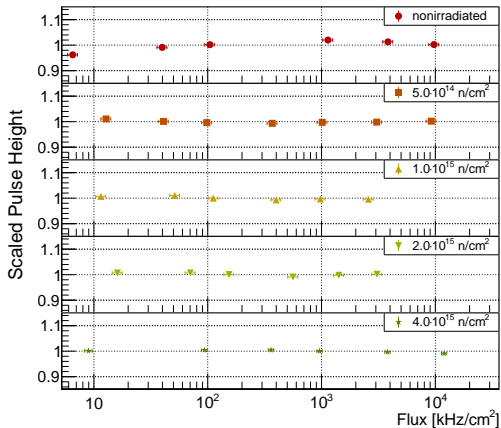
- uniform signal distribution in scCVD
- region dependent signal in pCVD

Silicon Diode



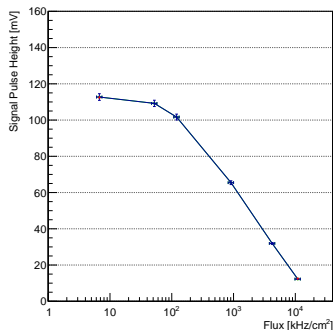
- silicon diode as reference
- as expected no dependence on rate

Rate Studies in Irradiated pCVD

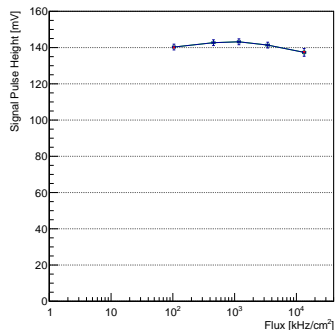


- rate scaled to the mean
- pulse height very stable after irradiation
- noise stays the same

Rate Dependence



(a) First measurement



(b) After reprocessing

- less than 20 % of the tested diamonds show rate dependence $>10\%$
- very large rate dependence at the first measurement ($>90\%$)
- after reprocessing and surface cleaning with RIE very stable behaviour ($\sim 2\%$)
- feasible to “fix” bad diamonds

Section 5

Conclusion

Conclusion

- strongly improved fabrication of 3D diamonds
 - ▶ 40x more cells
 - ▶ smaller cell size
 - ▶ smaller columns
- 3D Detectors work well in pCVD diamond
 - ▶ 99.2 % efficiency
 - ▶ nearly full charge collection
- rate tests of irradiated pCVD diamonds up to $4 \cdot 10^{15} \text{ n/cm}^2$
- irradiated pCVD diamond does not show rate dependence to $\mathcal{O}(2\%)$
- possible to repair pCVD diamonds with surface issues

Section 6

Outlook

Outlook

- results of $3.5 \cdot 10^{15} \text{ n/cm}^2$ irradiated $50 \mu\text{m} \times 50 \mu\text{m}$ detectors
- continue irradiation up to $1 \cdot 10^{16} \text{ n/cm}^2$
- test both $50 \mu\text{m} \times 50 \mu\text{m}$ and $25 \mu\text{m} \times 25 \mu\text{m}$ pixel detectors
- reduce cell 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

DEL FIN

