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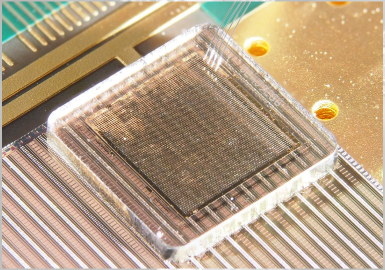

New Test Beam Results of 3D and Pad Detectors Constructed with Poly-Crystalline CVD Diamond

Vienna Conference on Instrumentation

Michael Reichmann on behalf of the RD42 Collaboration

19th of February, 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
- $\rightarrow$ **CERN R&D for more radiation tolerant detector designs and/or materials**

Diamond as Detector Material

- innermost tracking layers → highest radiation damage $\mathcal{O}\left(\text{GHz/cm}^2\right)$
- current detectors is designed to survive ∼12 month in High-Luminosity LHC
- → **CERN 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 $1 \cdot 10^{16}$ n/cm^2 the mean drift path in diamond larger than in silicon**

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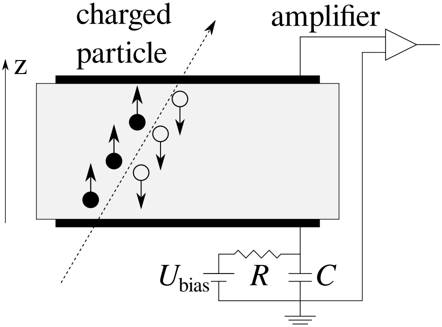
Work of RD42:

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

Section 2

Introduction

Diamond as Particle Detector

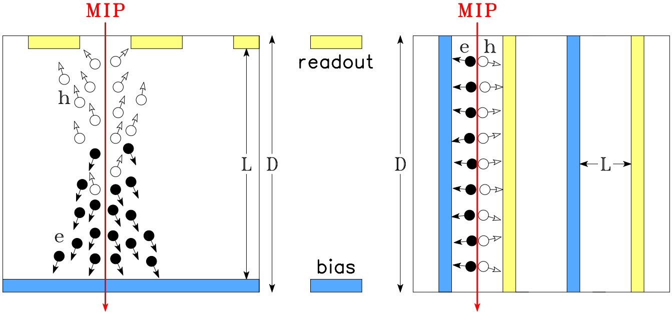


(a) Detector Schematics

(b) 15 cm ⌀ pCVD Diamond Wafer

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

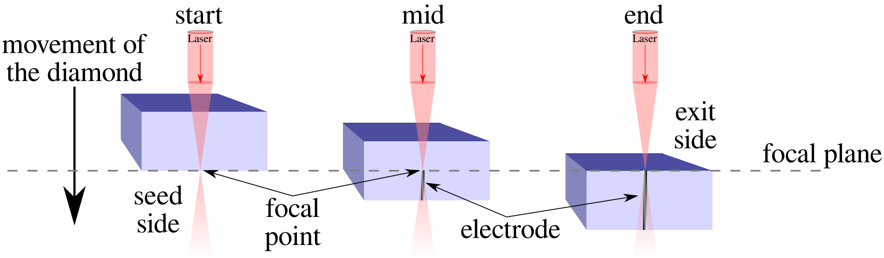
Working Principle



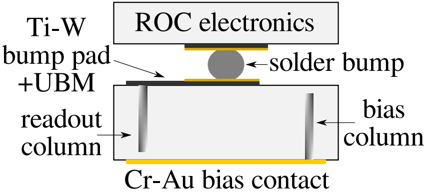
- after large radiation fluence all detectors become trap limited
- bias and readout electrode inside detector material
- same thickness D → same amount of induced charge → shorter drift distance L
- **increase collected charge in detectors with limited mean drift path (Schubweg)**

Laser drilling

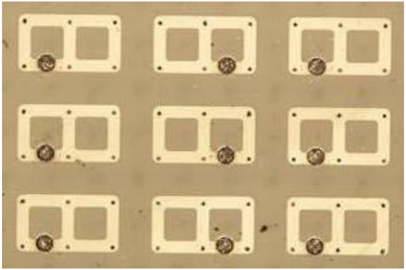
- “drilling” columns using 800 nm fs-LASER (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of Spatial Light Modulation (SLM) to correct for vertical aberration
- initial column yield $\sim$90 % $\rightarrow$ now $\geq$99 %
- initial column diameter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



Bump Bonding



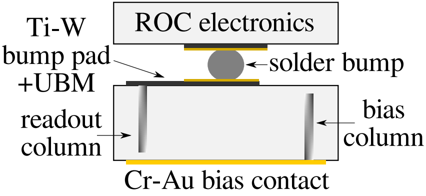
(a) Bump bond schematics



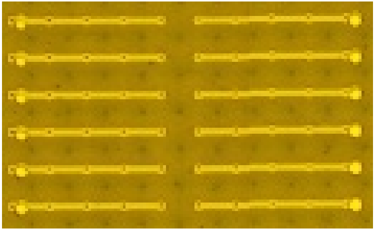
(b) 3 × 2 bump pads

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

Rate Studies in Pad Detectors:

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

Section 3

3D Pixel Detectors

1 × 5 Ganging

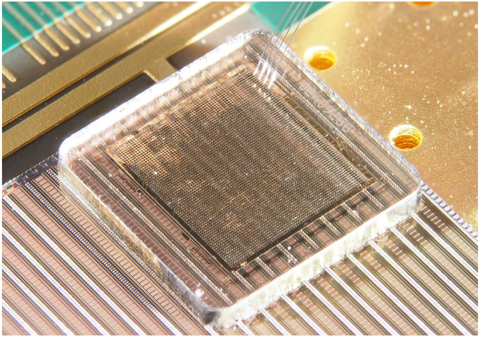
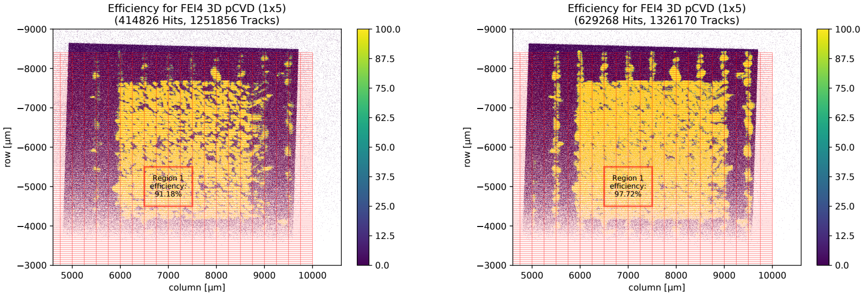


Figure: Final Detector

- readout chip (ROC): ATLAS FEI4 (50 μm × 250 μm)
- Size: 5 mm × 5 mm
- active area 3 mm × 3 mm
- tin-silver bump bonding at IFAE (Barcelona)

Efficiencies at CERN Beam Test



(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

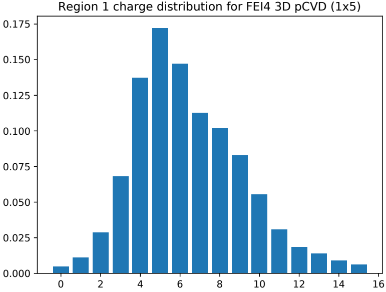


Figure: Time over threshold

- 5 tot $\approx$ 11 000 e
- mean of the ToT distribution: 6.73 $\rightarrow$ 14 800 e
- 81 % of the charge collected

2 × 3 Ganging

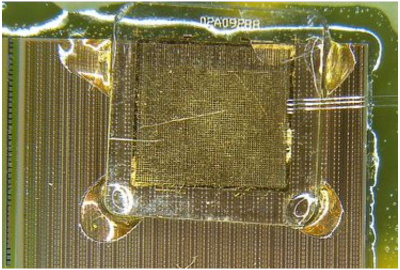
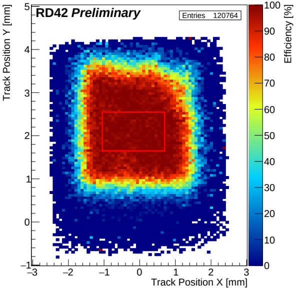


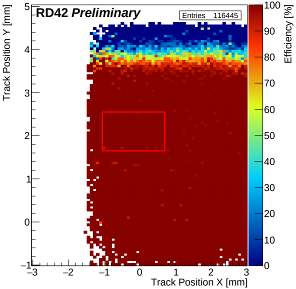
Figure: Final Detector

- readout chip (ROC): CMS PSI46digv2.1repspin (100 µm × 150 µm)
- Size: 5 mm × 5 mm
- active area 3.5 mm × 3.5 mm
- indium bump-bonding (Princeton)

Efficiencies - First PSI Beam Test



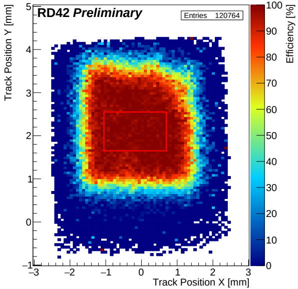
(a) Efficiency Map Diamond



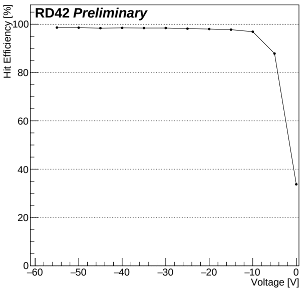
(b) Efficiency Map Silicon

- beam test right after the first bump bonding (top right corner badly bonded)
- spatial resolution of $\mathcal{O}\,(100\,\mu m)$
- 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

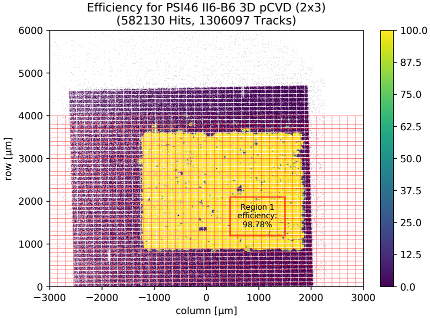
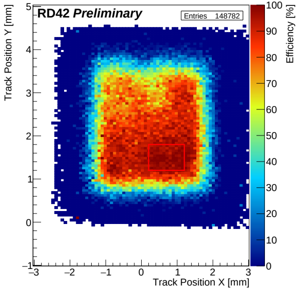


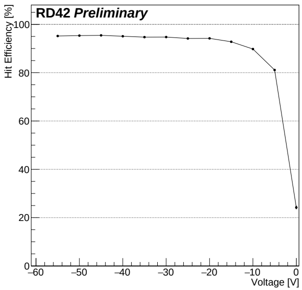
Figure: Efficiency at threshold of ∼3500 e

- 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

Efficiencies - Second PSI Beam Test



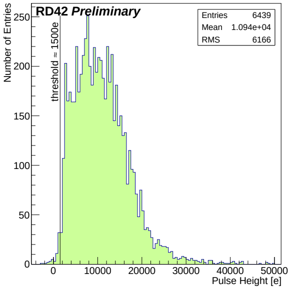
(a) Efficiency Map



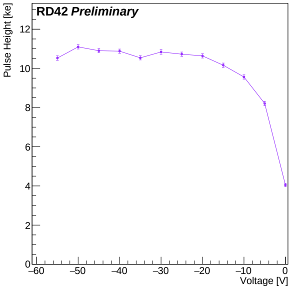
(b) Efficiency vs. voltage

- 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 → ≃14 000 e at CERN → consistent with 1 × 5 data

Section 4

Pad Detectors (Rate Studies)

Leakage Currents

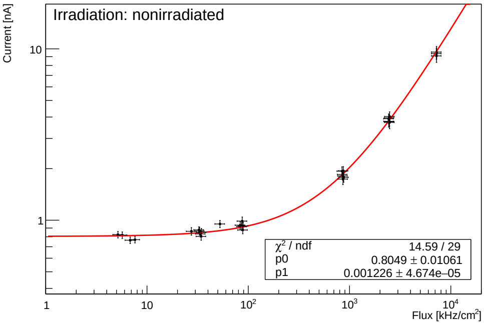
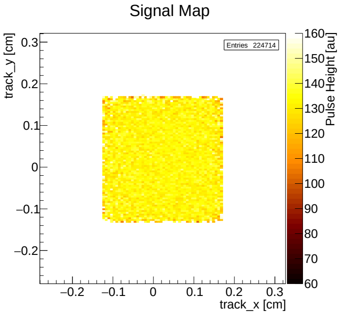


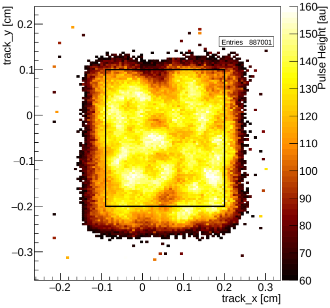
Figure: Leakage Current of a non-irradiated pCVD diamond

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

Signal Maps



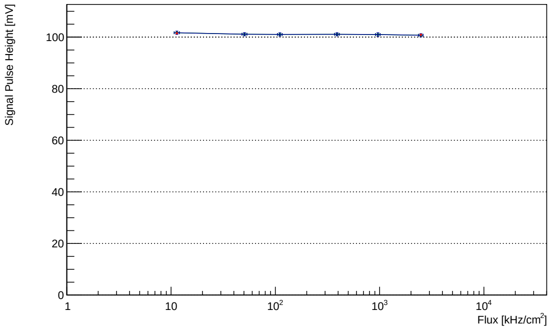
(a) scCVD (6 dB attenuation)



(b) pCVD

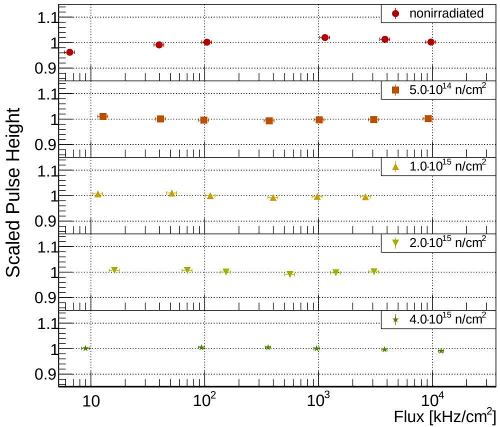
- uniform signal distribution in scCVD
- region dependent signal in pCVD

Silicon Diode



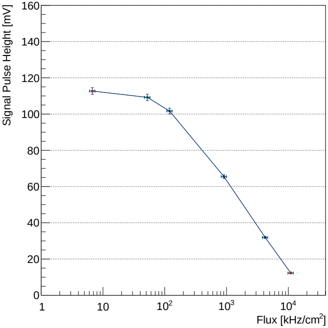
- silicon diode as reference
- as expected no dependence on rate

Rate Studies in Irradiated pCVD

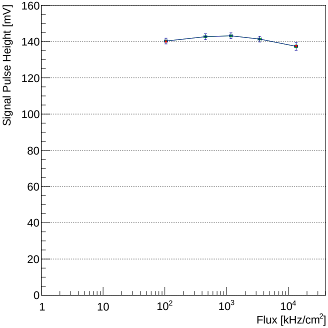


- rate scaled to the mean
- pulse height very stable after irradiation
- using rad hard electronics → noise stays the same

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 (∼2 %)
- feasible to "fix" bad diamonds

Section 5

Conclusion

Conclusion

- strongly improved fabrication of 3D diamonds
  - 40x more cells
  - smaller cell size
  - thinner columns
- 3D Detectors work well in pCVD diamond
  - 99.2 % efficiency
  - nearly full charge collection
- rate tests of irradiated pCVD diamonds up to $4 \cdot 10^{15}\,\mathrm{n/cm^2}$ and $20\,\mathrm{MHz/cm^2}$
- 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 $3.5 \cdot 10^{15}\,n/cm^2$ irradiated $50\,\mu m \times 50\,\mu m$ detectors
- continue irradiation up to $1 \cdot 10^{16}\,n/cm^2$
- test both $50\,\mu m \times 50\,\mu m$ and $25\,\mu m \times 25\,\mu m$ pixel detectors
- reduce column diameter to $1 \sim 2\,\mu m$
- build pixel device on newest RD53 chip ($50\,\mu m \times 50\,\mu m$ pixel pitch)
- continue scale up by 10x

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