Diamond as a solid state micro-fission chamber for thermal neutron detection

Michal Pomorski
CEA-LIST, Diamond Sensors Laboratory, France

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Trento
Co-Authors (CEA Saclay):
Christine Mer-Calfati
Francois Foulon

Many thanks to VR1 reactor team in Prague:
Lubomir Sklenka
Tomas Bily
Jan Rataj
and others.....

open access facility:
vyuka@ReaktorVR1.eu

request form:
reactorvr1.eu/download/request_for_access.pdf
Motivation / Previous work

Diamond Samples / Pre-testing

Set-up
- VR1 reactor in Prague
- U-235 + diamond detectors + electronics

Some results
- Fission fragments spectra
- Linearity with flux, core-mapping
- TCT signals + other observations

Summary
Motivation/Previous work
neutron detection with diamond detectors

Neutrons detection interests for diamond ...

- Energy range:
  - 25 meV
  - 1-2 MeV
  - 5.8 MeV
  - 14 MeV

- Neutron types:
  - Thermal neutrons
  - Fission neutrons
  - Elastic scattering
    - OK at high neutron fluencies
    - Typ. 1nA/cm² @ 10⁸n.cm⁻².s⁻¹ in a 100µm thick diamond layer
  - Nuclear reactors
    - Essentially when small size devices are required e.g. propulsion reactors
  - Fusion neutrons or DT confinement plasmas
  - Temporal metrology (TOF), Spectroscopy,
  - Tokamaks, Rochester, Laser Mega-Joule (LMJ)

- Bergonzo et al.
Motivation/Previous work

thermal neutron detection


<table>
<thead>
<tr>
<th>Isotope</th>
<th>Natural abundance (%)</th>
<th>( \sigma^* ) (barns)</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{6}\text{Li})</td>
<td>7.4</td>
<td>940</td>
<td>(^3\text{H}) (2.75 MeV) + (^4\text{He}) (2.05 MeV)</td>
</tr>
<tr>
<td>(^{10}\text{B})</td>
<td>19.8</td>
<td>3840</td>
<td>(^7\text{Li}) (1.0 MeV) + (^4\text{He}) (1.8 MeV) + (^7\text{Li}) (0.83 MeV) + (^4\text{He}) (1.47 MeV) + (\gamma) (0.48 MeV)</td>
</tr>
<tr>
<td>(^{157}\text{Gd})</td>
<td>15.7</td>
<td>255,000</td>
<td>(^{158}\text{Gd}) + (\gamma)s + conversion e(^{-}) + X-rays (29–182 keV)</td>
</tr>
<tr>
<td>(^{155}\text{Gd})</td>
<td>14.8</td>
<td>60,900</td>
<td>(^{156}\text{Gd}) + (\gamma)s + conversion e(^{-}) + X-rays (39–199 keV)</td>
</tr>
</tbody>
</table>

**Idea:**

Use of fissile material as a converter eg: Uranium–235 \(\rightarrow\) 584 barns for fission

Only one publication with FF and natural diamond (half page) ~ 1970...

+ previous work of Christine Mer et. al.

thick pcCVD+EGscCVD + high power reactor
**Optical Grade scCVD e6 (OGscCVD)**

- $[\text{NO}] \leq 1\text{ppm}$
- Thickness = 17 microns
- Size = 3 x 3 mm (broken)
- Contacts = Al (1mm diam.)

**p+-intrinsic-metal structure CEA (PIM)**

- $[\text{NO}] \ll 1\text{ppm}$
- Thickness ~ 20 microns (intr.)
- Size = 3 x 3 mm
- Contacts = Cr/Au (<1mm diam.)
Am-241 alpha spectra 5.486 MeV in vacuum, using CSA (3 micros shaping)

opt. scCVD ~17 µm @ +170 V (10 V/µm)

PiM @ +30 V (1.5 V/µm)
TCT (50 Ohm) from 5.48 MeV alphas, CIVIDEC

- optscCVD @ 170 V
- PiM @ 30 V

25%

buried p+

PIM, Claudio Verona Tor Vergata
Univ.Rome

Laser Pulse 220 nm
exp fit

~100ns

p+ on top

PiM @ 30 V

buried p+

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VR1 reactor in Prague

- low power research reactor (max 1kW, $1\times 10^9$ n/cm²s@500W)
- light water (reflector, shielding, cooling)
- no thermal effects....
U-235 + Diamond Detectors + Electronics

no collimator used

PiM

OGscCVD

1 cm

17 microns OG scCVD

5m of BNC

20 microns PiM scCVD

thermal neutrons

fission fragments

in-core

U-235

1 cm

bias voltages on read-out electrodes:
OGscCVD +170V(10V/micron) (h-drift)
PiM + 30V(~1.5V/micron) (h-drift)

DAQ

CSA

DAQ

CSA

V-1 Préparation des diamants et des convertisseurs

Les contacts en or (utilisés pour la caractérisation sous alpha) des diamants précaractérisés sont dissous (à l’aide d’une eau régale) puis redéposés par évaporation afin d’obtenir des plots de même surface.

Une couche de bore de 600 µm est déposée par évaporation au dessus d’une majeure partie du plot en or du diamant monocristallin T8 et du diamant CVD1 pour le diamant polycristallin. La partie du plot sans bore permettra de relier le fil en or afin de polariser le diamant. L’uranium ne peut pas être déposé par évaporation en raison de sa radioactivité. Il se présente sous forme de pastille sur laquelle est réalisé un dépôt d’uranium. La pastille est entourée de plastique, seul le dépôt est à nu.

FIG : Pastille d’uranium

Un support en téflon (non activable) à deux étages est réalisé pour le diamant T8 permettant de positionner un collimateur et la pastille d’uranium au dessus du diamant. Un autre support à un seul étage, pour la pastille d’uranium, est réalisé pour le détecteur CVD2.

Le collimateur permettra de collimater les fragments de fission issus de l’uranium pour le diamant monocristallin. En revanche, pour les diamants associés au bore, les neutrons ne peuvent pas être collimatés.

FIG : Support en téflon

V-2 Montage du boîtier

Les boîtiers sont en graphite (non activable), munis de deux trous pour pouvoir faire passer les câbles dénudés amenant la haute tension (HT) et permettant de récuperer les impulsions. Les diamants sont collés avec de la pâte à l’argent sur une plaque de circuit imprimé. Des « protections » en téflon sont positionnées sous le fil d’or pour éviter que celui-ci en collimator used
U-235 fission

average energy to fission fragments ~170 MeV

after 5mm air (rough estimation)
~80 MeV Kr (~110 MeV)
~35 MeV Ba (~60 MeV)

+ alpha decay with 4.679 MeV

Ba-56@60MeV

Kr-36@110MeV
Fission Fragments Spectra

- Gamma background
- Heavier FF/Lower E
- Lighter FF/Higher E

Normalized counts vs. channel number

- OGscCVD
- PIM

Average energy to fission fragments: ~170 MeV

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Fission Spectra with Increasing Power

OGscCVD

PiM

~ 10 min acquisition time

alpha-peak@~4.679MeV

100W ~ 2E9 n/cm2.s (core center)
Linearity with Flux

**OGscCVD**

- Threshold @ 200 ch
- $\sigma0.7\%$
- $R^20.9997$

**PiM**

- $\sigma0.3\%$
- $R^20.9999$

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Core-Mapping

@100W

OGscCVD

PiM

distance from the channel bottom [cm]

integrated counts diamond detector

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@100W

**OGscCVD + PiM**

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**OGscCVD + PiM + He3**

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Gamma Background

**OGscCVD**

- 100 W
- 10 W
- 1 W

**PiM**

- 1 W
- 10 W
- 100 W
TCT Signals for OGscCVD

350 MHz DSO@50 Ohm + 5m BNC

CIVIDEC 40dB amplifier

no amp, just bias-T

| y 100mV/div ; x 10ns/div | y 2mV/div ; x 5ns/div |
Some More Observations

Priming of OGscCVD

$\gamma$-priming (?)

$^{235}$U $\alpha$-particles 4.679 MeV

OGscCVD

PiM (no priming)
Polarisation of OGscCVD@-170V majority of e-drift

Some More Observations

strong electron trapping in OGscCVD....

final state (stable)
From previous work, Christine Mer et al MonoX=EGscCVD ~200 microns thick

Relative decrease of the position pic % vs neutron fluence (neutron/cm²)

- Polycrystalline diamond with boron converter
- Polycrystalline diamond with Uranium converter
- Single crystal diamond with Uranium converter

should be better for thin detectors, and even better for membranes……….
Summary and Outlook

What can be 'easily' improved:

- sensitivity/count rate x100 —> larger samples+contact size+sandwich conf.
- larger TCT signals —> better electronics, U-235 precipitation on diamond
  - (Philippe talk)
- better gamma/neutron ratio —> U-235 electro-precipitation on diamond
- improved RH —> membrane OGscCVD, thinner i-layer = no implantation

some open questions:

- sensitivity, RH

What can be 'easily' improved:

- use of U-235 as converter material - with FF of high energy
- diamond micro-fission chamber based on 'cheap' OG material concept proved:
  - stable operation (FF up to 5kHz tested), perfect linearity
  - high n/gamma ratio
  - possibility to operate with no amps...maybe HTemp etc......
First Applications

In-core thermal neutron monitoring

Diamond as micro solid-state fission chamber:

VR1 training reactor in Prague

facility with open access please
contact: lubomir.sklenka@fjfi.cvut.cz

U-235 - lower crosssection, but heavy fragments
large signal, better n/gamma ratio, no-amplification needed

VR1 training reactor in Prague
First Applications
In-core thermal neutron monitoring

Easy to optimise:
- U-235 deposition onto diamond
- Thinner membrane (RH, gamm/n)
- Larger surface, sandwiching (sens.)

**235U Fission Fragments**

- A ≈ 95
- A ≈ 137
- A ≈ 118

**235U** alpha 4.679 MeV

**Typical spectra of fission products**

- OGD diamond
- PIM

**Gamma background**

- 100 W
- 10 W
- 1 W

**Varying reactor power (acq. 10 min)**

- 500 W
- 100 W
- 10 W
- 1 W
- 0.1 W
- 0.01 W

**Linearity vs. reactor diagnostics**

- Threshold = 200 ch
- 0.7%

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Thanks for your attention!
UV 337nm laser TCT Photovoltaic Mode (zero-bias)

Electronic Properties

- \( \Delta E \)
- \( \text{membrane} \)
- 50 Ohm
- DSO
- laser absorption
- p-doped
- \( \text{OD filters} \)
- \( \text{QE} \approx 10^{-5} \)

TCT signals

- Signal amplitude on 50 Ohm [V]
- Time [ns]

- UV 337nm, 2.5 ns pulse ~100\( \mu \)W
- Nitrogen laser, trigger

Claudio Verona Tor Vergata Univ. Rome

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First Application
PIM Membrane ‘Dosimetry’

Methyl Viologen chemical dosimeter

PIM membrane ‘dosimeter’
First Application

Zero-Bias Compared to 'Normal' Operation (bias-T - 20V applied)

1 μs e-pulse

-1x10^-6 0.0 1.0x10^-6 2.0x10^-6 3.0x10^-6

time [s]

signal amplitude on 50 Ohm [V]

0 1 2 3 4 5

-1.0x10^-6 0.0 1.0x10^-6 2.0x10^-6 3.0x10^-6

time [s]

induced current [A]

0 0.02 0.04 0.06 0.08 0.10

signal amplitude on 50 Ohm [V]

-1 0 1 2 3 4 5

-1.0x10^-6 0.0 1.0x10^-6 2.0x10^-6 3.0x10^-6

time [s]

signal amplitude on 50 Ohm [V]

-1 0 1 2 3 4 5

0 0.1 0.2 0.3 0.4 0.5

-1.0x10^-6 0.0 1.0x10^-6 2.0x10^-6 3.0x10^-6

time [s]

-20V 0V

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