X-ray induced photocurrent characteristics of diamond detectors with different amorphous carbon electrodes

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Talk Outline

Motivation

The need of low thickness / low atomic number electrodes

Device Fabrication

Free metal amorphous carbon electrodes by Pulsed Laser Deposition

X-ray characterization (laser fluence dependence study)

Definition of optimal bias, Leakage current, IV characteristics, Linearity

Conclusions

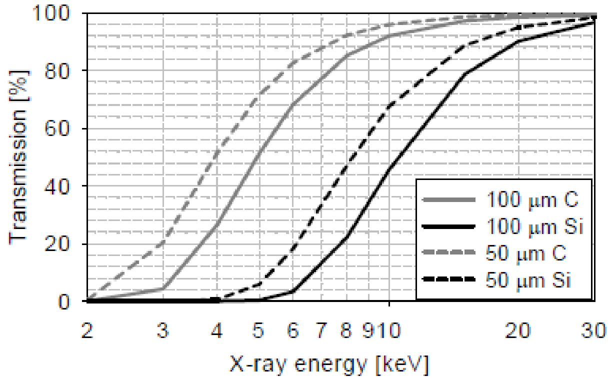
Is Pulsed Laser Deposition a reliable method? Any issues to be solved?

Motivation

Synthetic diamonds are of interest in a broad range of detection applications.

X-ray dosimetry: atomic number of Z=6 (near tissue equivalent).

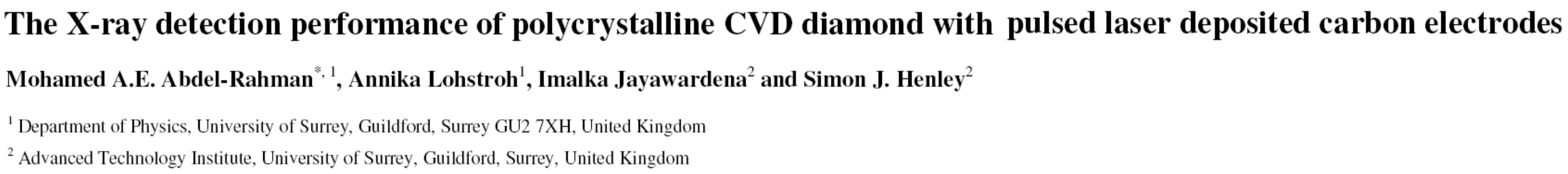
Beam monitors: radiation hardness, low atomic number (low perturbation and absorption of the incident beam).



Low thickness / low atomic number electrodes become an absolute requirement!

Pulsed Laser Deposition (PLD)

PLD technique can be used to produce free-metal amorphous carbon coatings as electrode material for diamond detectors.



The X-ray detection performance of polycrystalline CVD diamond with pulsed laser deposited carbon electrodes

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Advantages:

- deposited ions and atoms impinge onto the substrate surface with sufficient energy (> 100 eV) giving better adhesion and mechanical stability of the layer.

- it allows to create ad-hoc amorphous carbon layers having determined structure in terms of sp^2/sp^3 ratio, conduction mechanism and electrical/optical properties.

The aim of this study is to optimize the PLD layer deposition on one electronic grade pcCVD sample and then, based on the results achieved with X-ray characterization, to develop a single crystal diamond device with optimized carbon electrodes.

PLD - Equipment

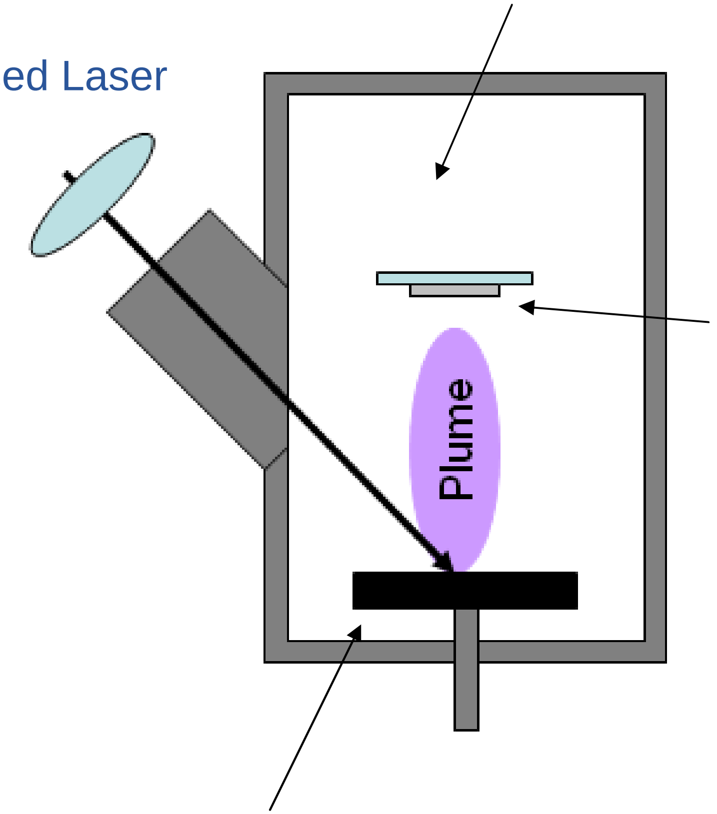
The LPX's dependable design allows for various applications such as high precision micromachining, ink jet nozzle drilling, optical material testing, spectroscopy and photochemistry.

λ = 248 nm

Pulse duration = 25 ns

Max pulse energy ~ 1 J

Max repetition rate = 200 Hz



Chamber pumped to 10^{-6} Torr (with option of back filling with gas)

Pulsed Laser

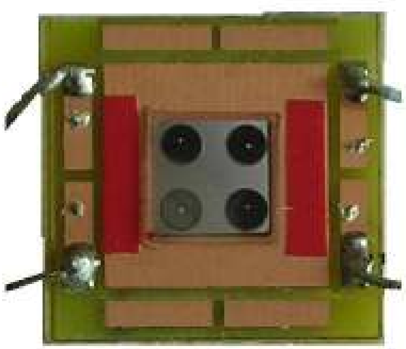
Substrate

Target - Rotates and translates to avoid repeated ablation of the same spot

Device Fabrication

Electronic Grade pcCVD sample of dimensions: 10x10x0.5 mm^3

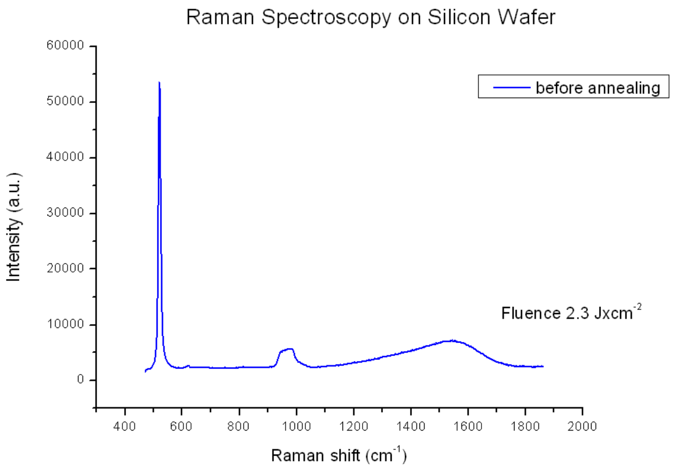
Device	Diameter (mm)	Side 1 Type	Thickness (nm)	Side 2 Type	Fluence ($Jxcm^{-2}$)	Thickness (nm)
1	3	Al/Au	70+30	Amorphous C	2.3	20
2	3	Al/Au	70+30	Amorphous C	2.8	20
3	3	Al/Au	70+30	Amorphous C	3.2	20
4	3	Al/Au	70+30	Amorphous C	3.6	20

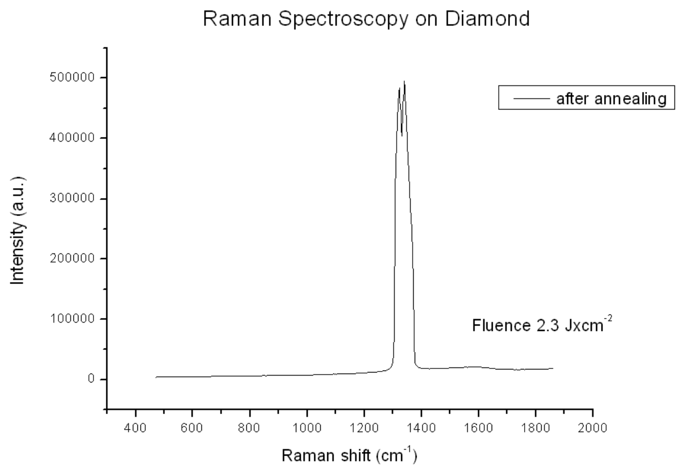


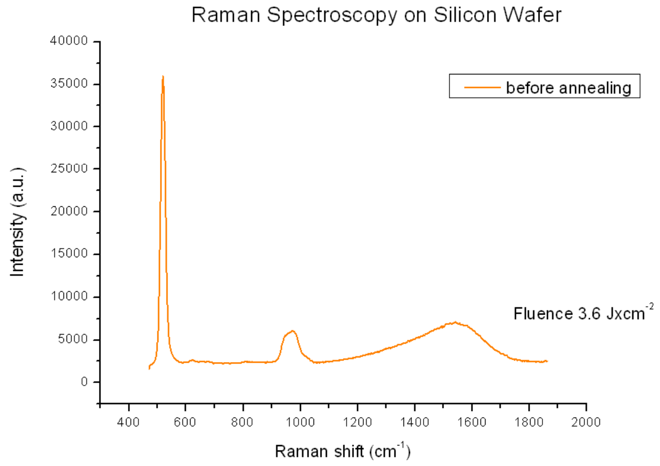
- Deposition of C contacts by PLD using a shadow mask
- Annealing at 500 ^{0}C for 5 min at the pressure of 10^{-2} Torr
- Deposition of Al/Au contacts on the back side by sputtering
- Mounting of the device on a drilled PCB (no use of silver paint!)
- Connection of the contacts by wire bonding using 25 μm gold wire

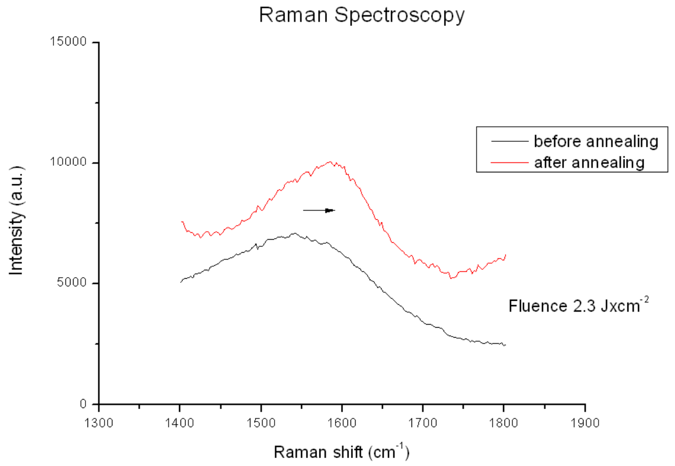
Fluence limited by the poor adhesion of the C contacts on the diamond surface

Contacts Characterization by Raman



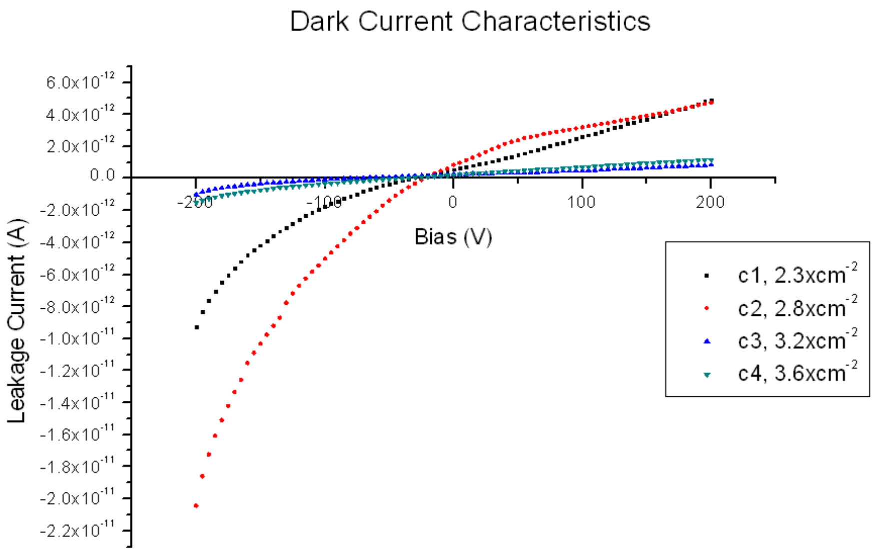




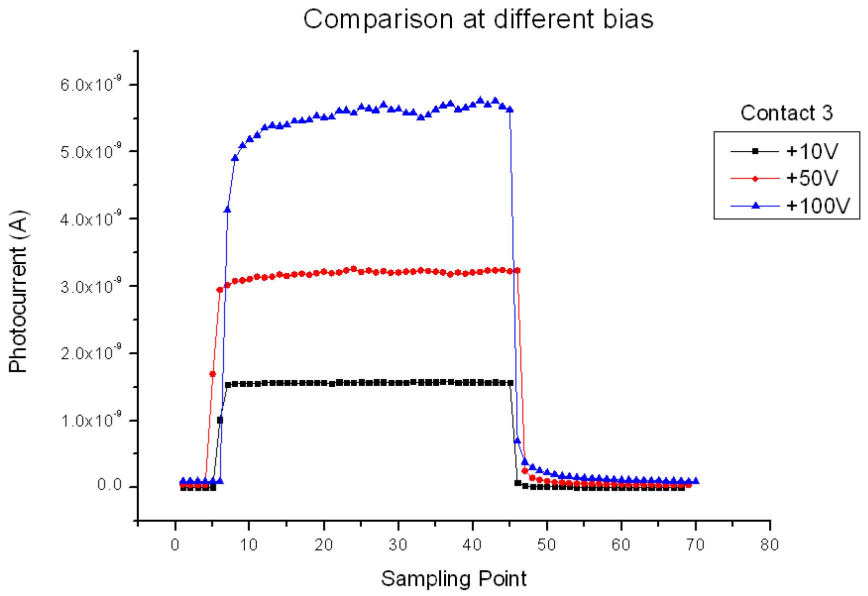


Raman spectroscopy was carried out using a Renishaw MicroRaman system at the wavelength of 514.5 nm.

Leakage Current & Optimal Voltage



Dark Current Characteristics

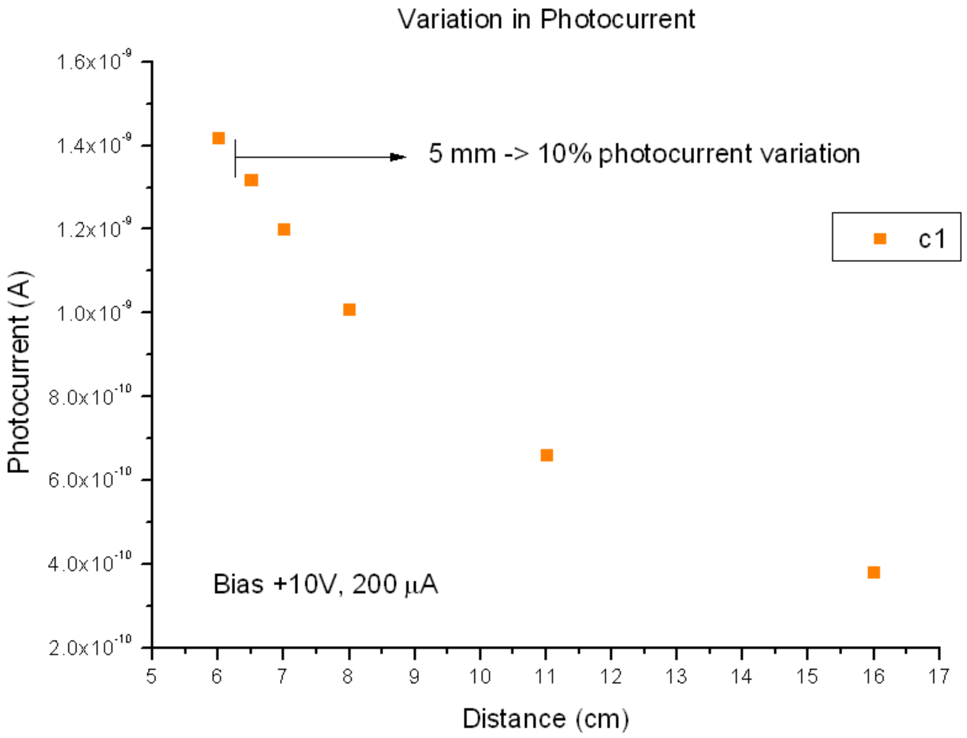


Comparison at different bias

- The leakage current did not exceed 20 pA for the maximum voltage applied.
- I(±100 V) ~ 5 pA leading to a minimum bulk resistivity of $2.8\cdot10^{14}$ Ω·cm.

- Best dynamic performances under radiation at +10 V (rise time, fall-off time ~2 s).
- At bias > 50 V the photocurrent is not stable and prevents the use of the detectors.

Photocurrent variations



Experimental parameters:

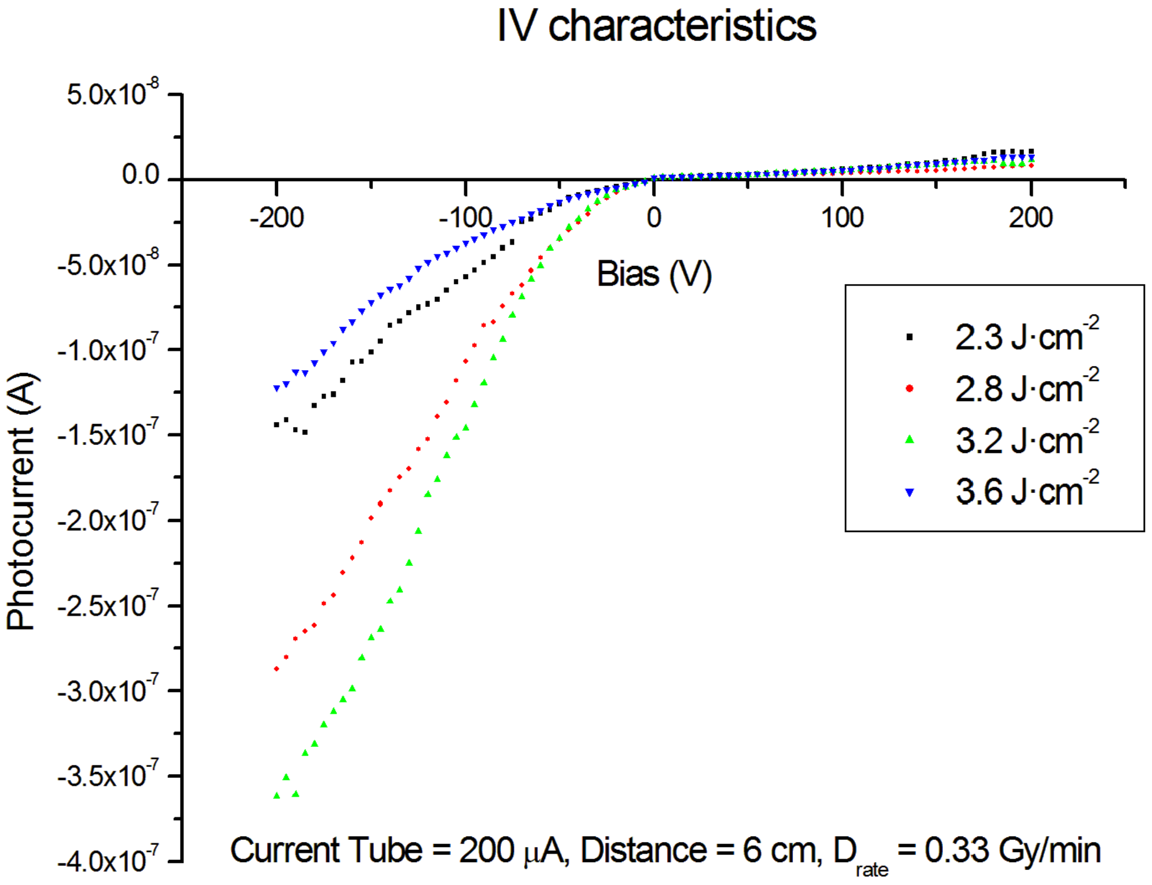
distance = 6 cm;
Tube current I_t = 200 µA;
D_{rate} = 0.33 Gy/min

Dose rate was assessed by a 0.6 cm^3 ionization chamber Mod. NE2571A.

Each front electrode was carefully centred and placed at 6 cm from the X-ray source.

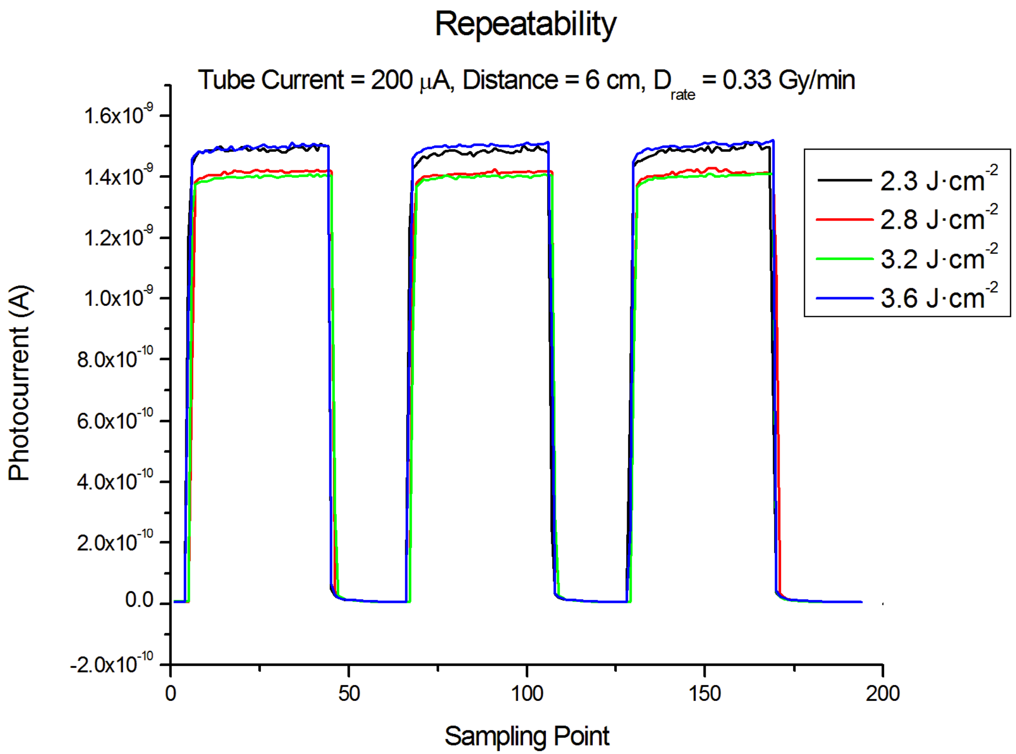
The dosimetric characterization that follows has to be considered as a preliminary test since it spans over a narrow range of energies and dose rates.

IV characteristics



For positive voltage the contacts show a blocking behaviour which becomes quasi-ohmic when a negative bias is applied.

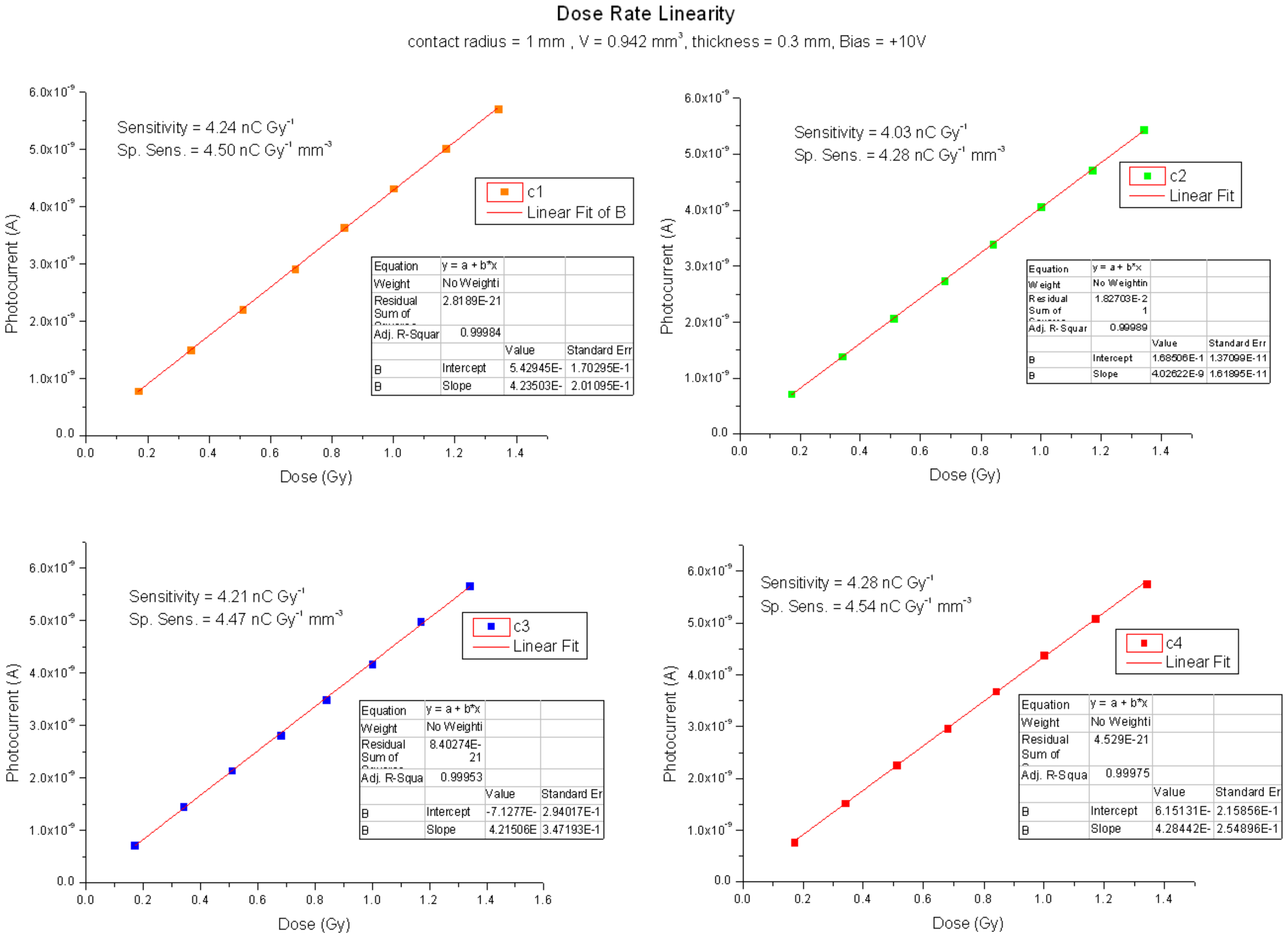
Reproducibility



Photoconductive Gain $Gain = \frac{I_{measured}}{I_{generated}} = \frac{\tau}{T_r}$ $I_{generated} = \frac{D\rho e v}{w}$ → ~ 0.3

Reproducibility $Reproduciblity = \left[\left(\frac{SD}{average} \right) \times 100 \right] \%$ → < 0.5

Dose Rate linearity



Dose Rate Linearity

contact radius = 1 mm , V = 0.942 mm^3, thickness = 0.3 mm, Bias = +10V

Sensitivity = 4.24 nC Gy^{-1}
Sp. Sens. = 4.50 nC Gy^{-1} mm^{-3}

Equation	y = a + b*x		
Weight	No Weighti		
Residual Sum of	2.8189E-21		
Adj. R-Squar	0.99984		
		Value	Standard Err
B	Intercept	5.42945E-	1.70295E-1
B	Slope	4.23503E-	2.01095E-1

Sensitivity = 4.03 nC Gy^{-1}
Sp. Sens. = 4.28 nC Gy^{-1} mm^{-3}

Equation	y = a + b*x		
Weight	No Weightin		
Residual Sum of	1.82703E-21		
Adj. R-Squar	0.99989		
		Value	Standard Err
B	Intercept	1.68506E-1	1.37099E-11
B	Slope	4.02622E-9	1.61895E-11

Sensitivity = 4.21 nC Gy^{-1}
Sp. Sens. = 4.47 nC Gy^{-1} mm^{-3}

Equation	y = a + b*x		
Weight	No Weighti		
Residual Sum of	8.40274E-21		
Adj. R-Squa	0.99953		
		Value	Standard Er
B	Intercept	-7.1277E-	2.94017E-1
B	Slope	4.21506E	3.47193E-1

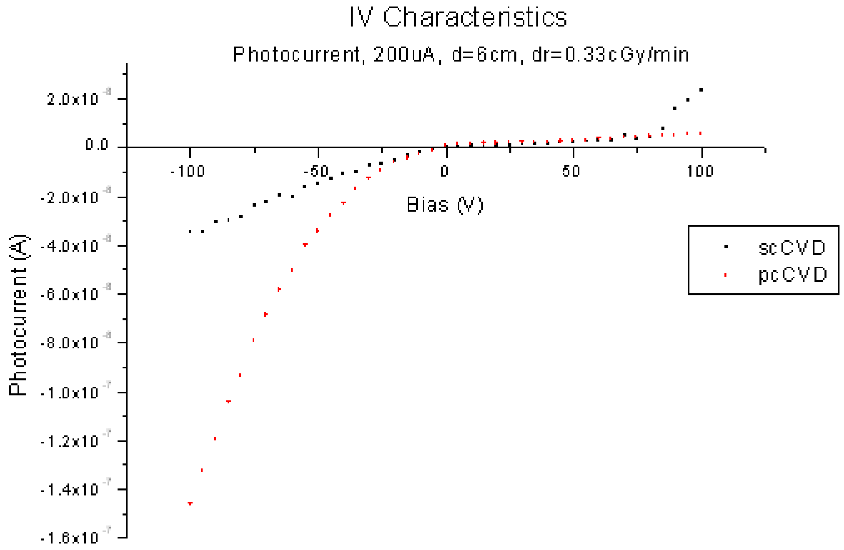
Sensitivity = 4.28 nC Gy^{-1}
Sp. Sens. = 4.54 nC Gy^{-1} mm^{-3}

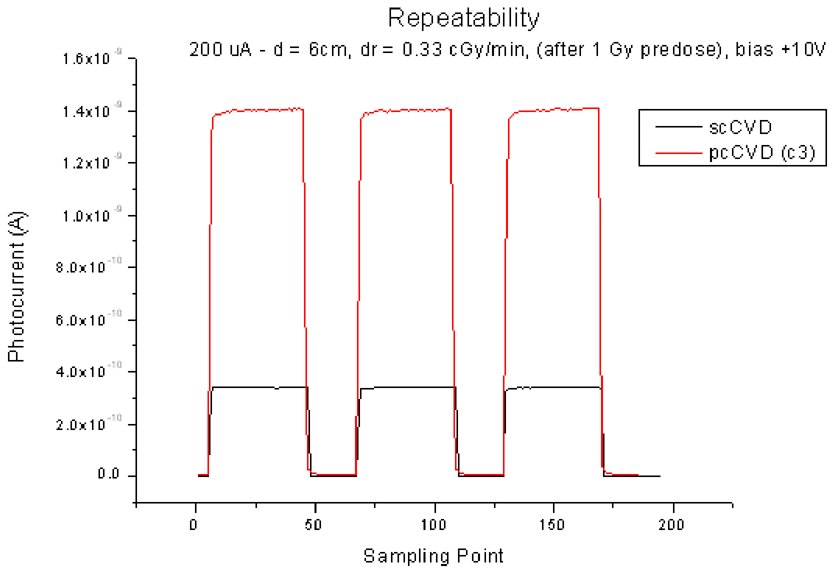
Equation	y = a + b*x		
Weight	No Weighti		
Residual Sum of	4.529E-21		
Adj. R-Squa	0.99975		
		Value	Standard Er
B	Intercept	6.15131E-	2.15856E-1
B	Slope	4.28442E-	2.54896E-1

Fouler model $I = I_0 + cD^{\Delta} \Longrightarrow \Delta$~1

scCVD Diamond Detector

Device	Diameter (mm)	Side 1 Type	Thickness (nm)	Side 2 Type	Fluence (Jxcm^{-2})	Thickness (nm)
pc1	3	Al/Au	70+30	Amorphous C	2.3	20
pc2	3	Al/Au	70+30	Amorphous C	2.8	20
pc3	3	Al/Au	70+30	Amorphous C	3.2	20
pc4	3	Al/Au	70+30	Amorphous C	3.6	20
sc	2	Amorphous C	20	Amorphous C	3.2	20





scCVD Diamond Detector

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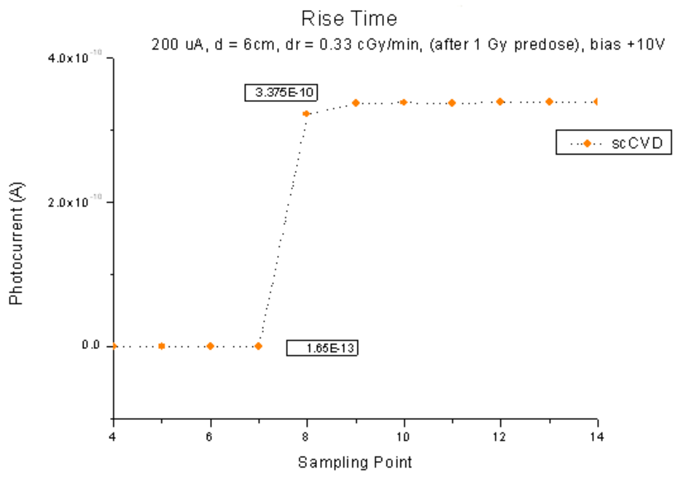
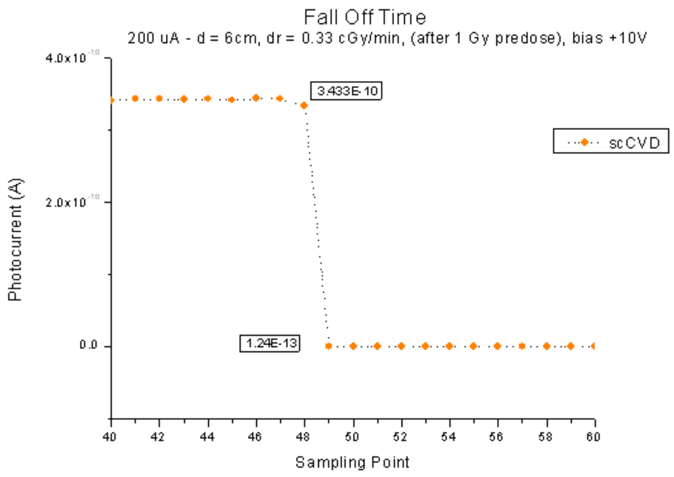


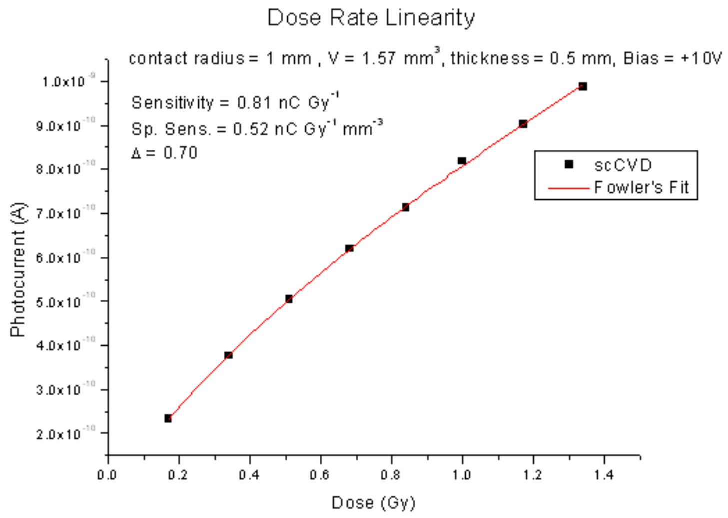
Rise Time

200 uA, d = 6cm, dr = 0.33 cGy/min, (after 1 Gy predose), bias +10V



Fall Off Time

200 uA - d = 6cm, dr = 0.33 cGy/min, (after 1 Gy predose), bias +10V



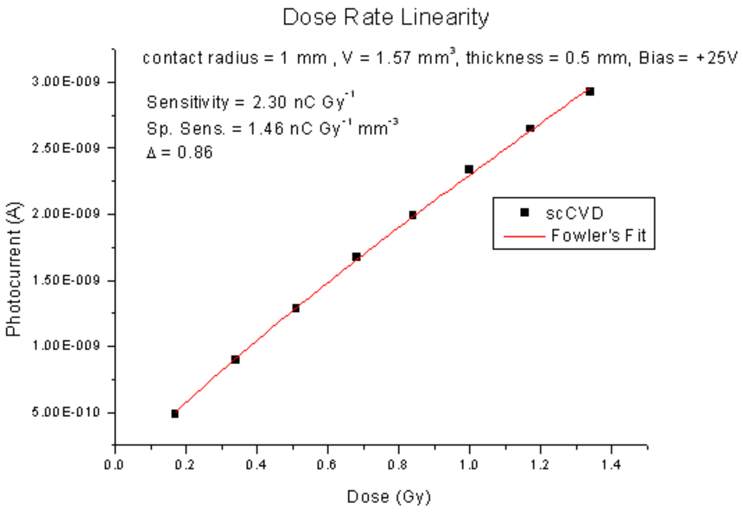
Dose Rate Linearity

contact radius = 1 mm , V = 1.57 mm^3, thickness = 0.5 mm, Bias = +10V

Sensitivity = 0.81 nC Gy^{-1}

Sp. Sens. = 0.52 nC Gy^{-1} mm^{-3}

Δ = 0.70



Dose Rate Linearity

contact radius = 1 mm , V = 1.57 mm^3, thickness = 0.5 mm, Bias = +25V

Sensitivity = 2.30 nC Gy^{-1}

Sp. Sens. = 1.46 nC Gy^{-1} mm^{-3}

Δ = 0.86

Comparison of Diamond Detectors

	PC CVD 1 (2.3 J·cm^{2})	PC CVD 3 (3.2 J·cm^{2})	SC CVD (3.2 J·cm^{2})
Bias (V)	+10	+10	+10
I_{meas} (A)	$1.49\cdot10^{-9}$	$1.40\cdot10^{-9}$	$3.41\cdot10^{-10}$
I_{dark} (A)	$5.37\cdot10^{-12}$	$4.82\cdot10^{-12}$	$1.50\cdot10^{-13}$
I_{gen}	$5\cdot10^{-9}$	$5\cdot10^{-9}$	$2\cdot10^{-9}$
Gain	0.30	0.28	0.17
Rise Time (s)	2	2	1
Sens. (nC/Gy)	4.24	4.21	0.81
Δ	0.98	1.00	0.70
Signal/Noise	277	290	2200

Conclusions

We developed pc/sc CVD diamond detectors based on metal-free amorphous carbon contacts fabricated by PLD. The devices showed very promising dosimetric properties (but at limited bias voltage!).

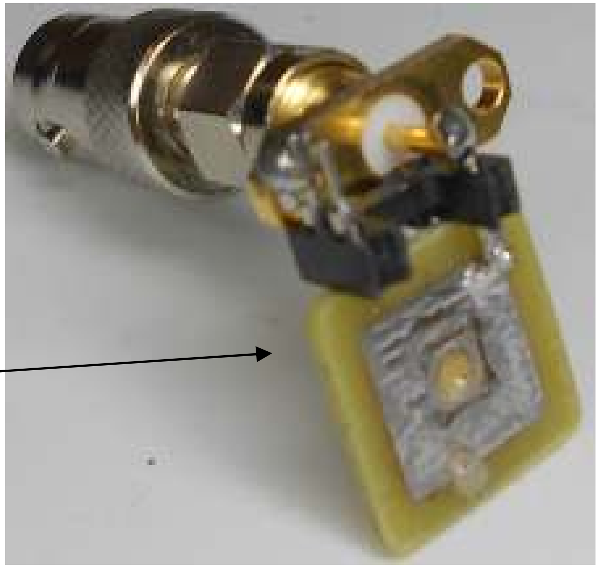
Although carbon electrodes were fabricated at different laser fluences, the diamond detectors showed very similar behavior. This might suggest that:

- the fluence interval used to fabricate the carbon layers was too short to appreciate remarkable changes on the dosimetric properties of the devices or
- subsequent annealing of the samples ultimately controls the final conductivity

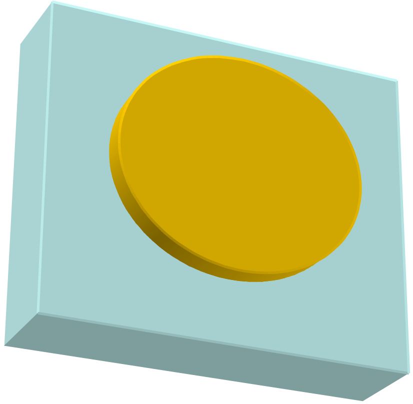
Either way, it suggests that the PLD method produces carbon electrodes with high repeatability.

Future work

- to understand what causes the limitation in the bias applied
- to investigate a broader range of laser fluencies
- device characterization nrrds to be extended in a broader range of X-ray energies and dose rates



Low-Area Plug&Play PCB



Sample Thickness ~ 90 µm

Contacts 70 Al + 20 Au nm; d = 2.5 mm

Deposition method: thermal evaporation

Bonding onto PCB by 25 µm gold wire

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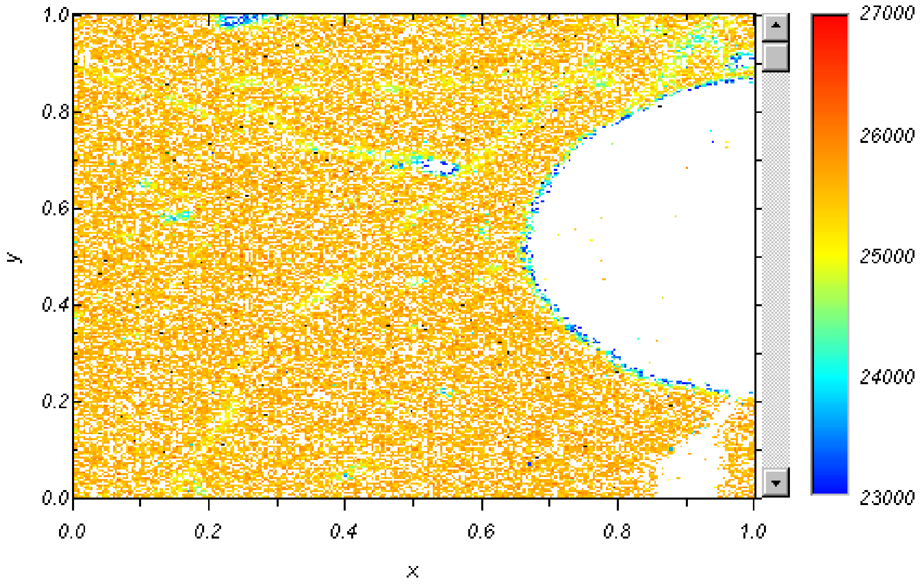
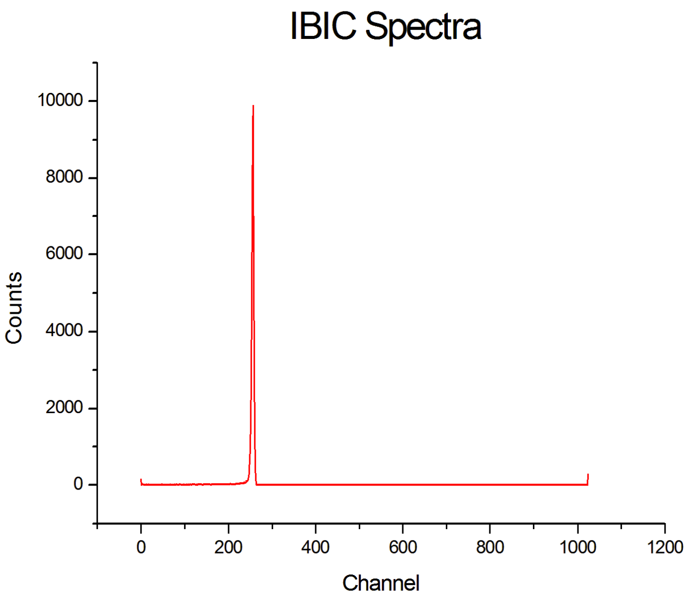
IBIC measurments





Resolution achieved 2% (commercial diamond detector 1.5%)

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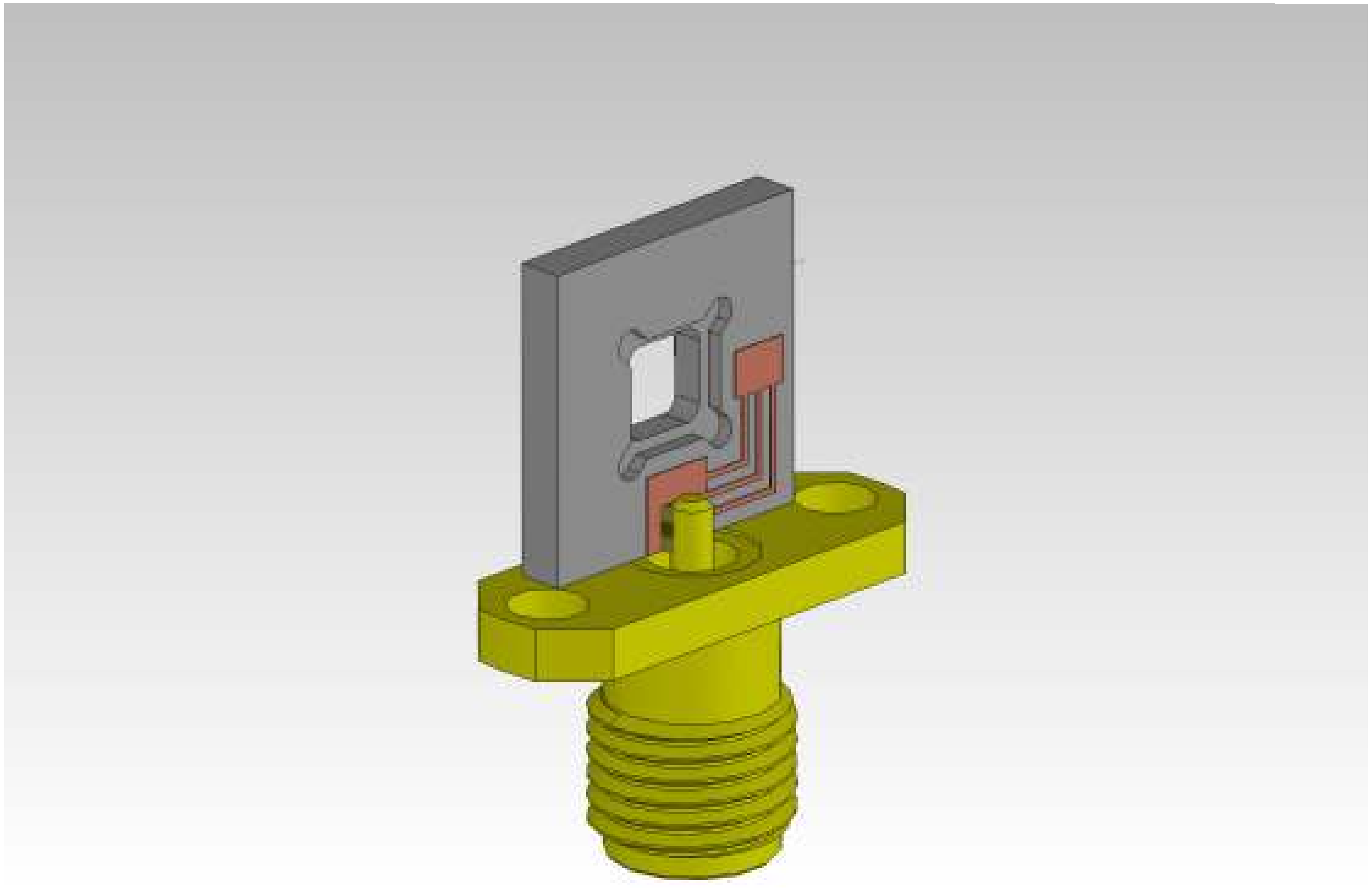
New PCB design



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Current Pulses from Alpha source

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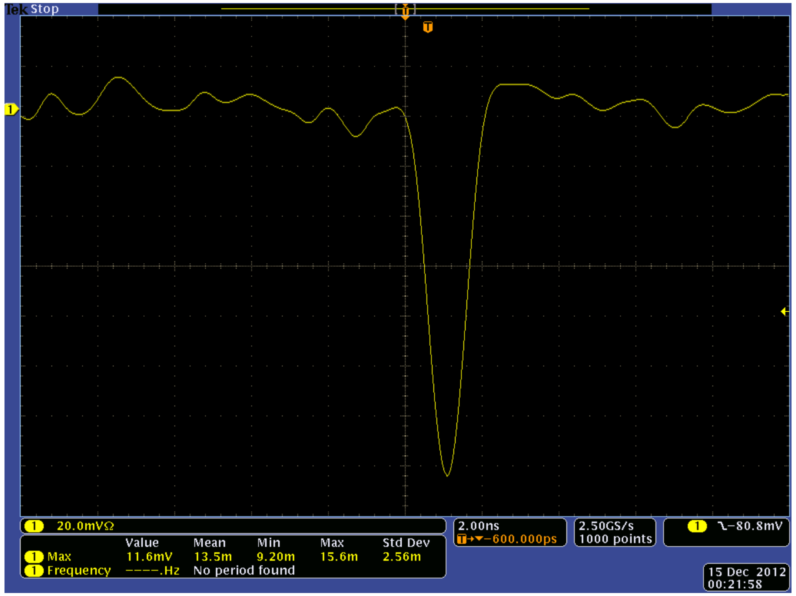

```
1  20.0mVΩ                                        2.00ns          2.50GS/s       1  ∖-80.8mV
             Value    Mean    Min     Max     Std Dev   T→▾-600.000ps   1000 points
1 Max        11.6mV   13.5m   9.20m   15.6m   2.56m
1 Frequency  ----.Hz  No period found                                             15 Dec 2012
                                                                                  00:21:58
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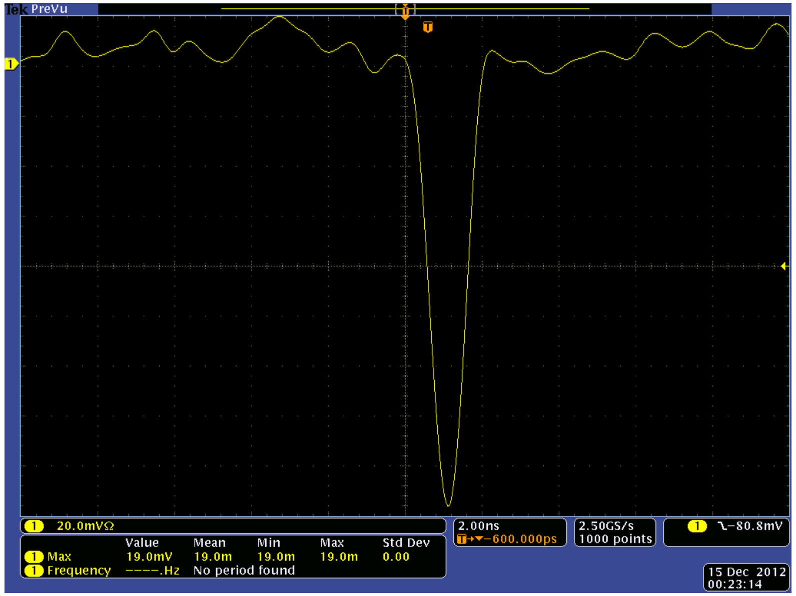

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1  20.0mVΩ                                        2.00ns          2.50GS/s       1  ∖-80.8mV
             Value    Mean    Min     Max     Std Dev   T→▾-600.000ps   1000 points
1 Max        19.0mV   19.0m   19.0m   19.0m   0.00
1 Frequency  ----.Hz  No period found                                             15 Dec 2012
                                                                                  00:23:14
```

Contacts 70 Al + 20 Au nm; d = 2.5 mm

Deposition method: thermal evaporation

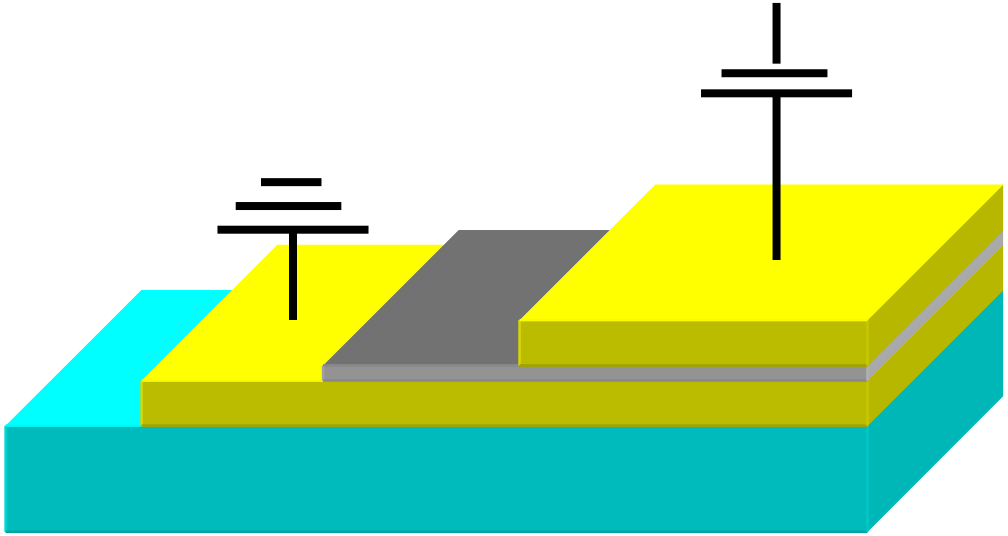
Contacts 50 nm Au; d = 2.5 mm

Deposition method: sputtering

Future plan

- development of scCVD with possibly increased contact thickness (30 nm?) and its characterisation under x-ray and alpha source.

- Measurement of the amorphous C contact resistivity.

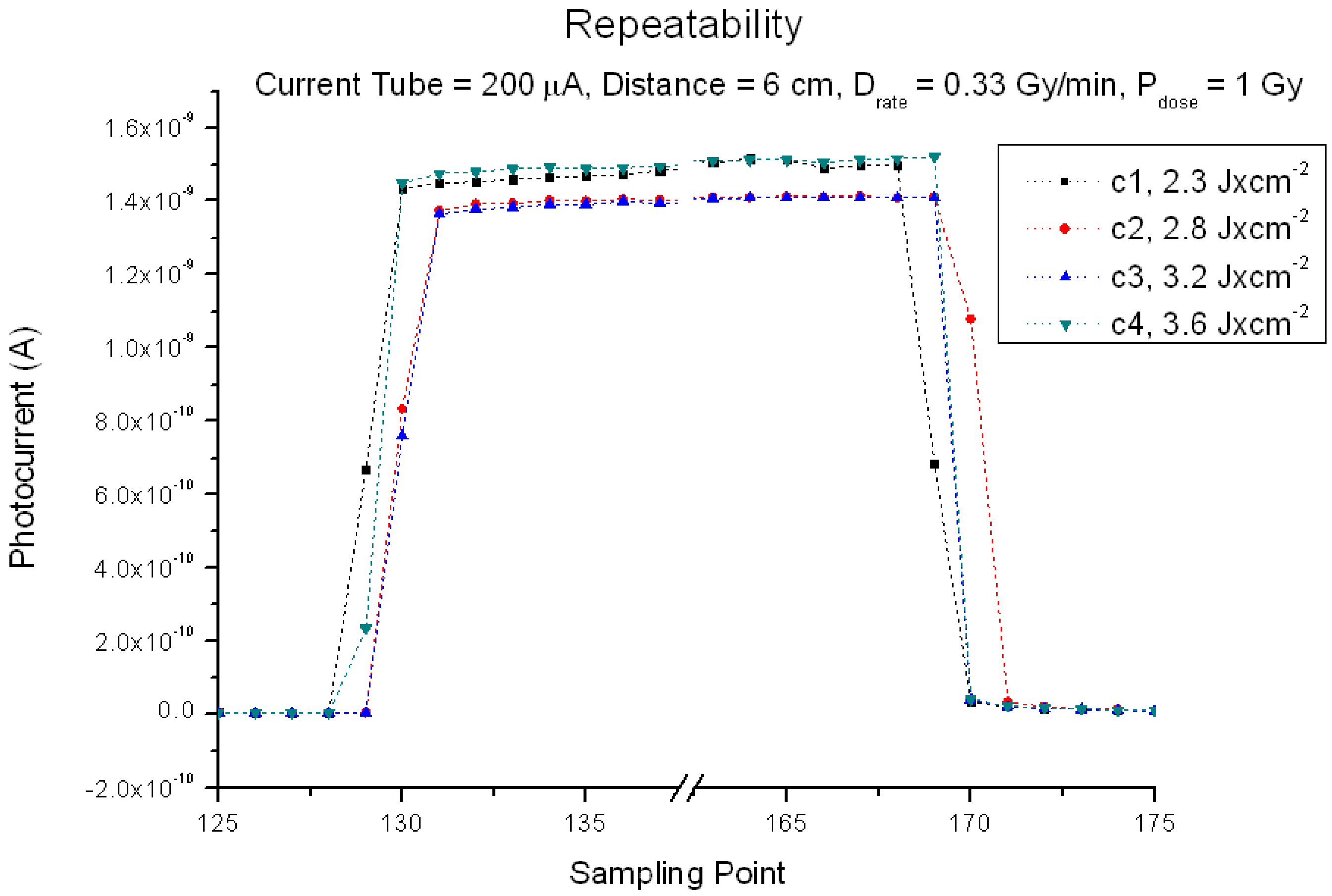


Reproducibility

Device Number	Cycle Number	Average current (A)	SD (A)	Reproducibility (%)
1	1	1.49039E-9	6.48527E-12	0.43514
	2	1.48347E-9	7.99994E-12	0.53927
	3	1.49104E-9	8.0025E-12	0.53671
	Σ	**1.4883E-9**	**7.4959E-12**	**0.50371**
2	1	1.41555E-9	6.33981E-12	0.44787
	2	1.412E-9	5.12426E-12	0.36291
	3	1.41776E-9	6.57191E-12	0.46354
	Σ	**1.4151E-9**	**6.01199E-12**	**0.42477**
3	1	1.3997E-9	5.70353E-12	0.40748
	2	1.40053E-9	3.99987E-12	0.2856
	3	1.40288E-9	3.33317E-12	0.23759
	Σ	**1.40104E-9**	**4.34552E-12**	**0.31022**
4	1	1.49658E-9	8.128E-12	0.54311
	2	1.503E-9	4.26539E-12	0.28379
	3	1.50524E-9	5.65155E-12	0.37546
	Σ	**1.50161E-9**	**6.01498E-12**	**0.40079**

The obtained values indicate low fluctuations in the signals

Rise & fall off times

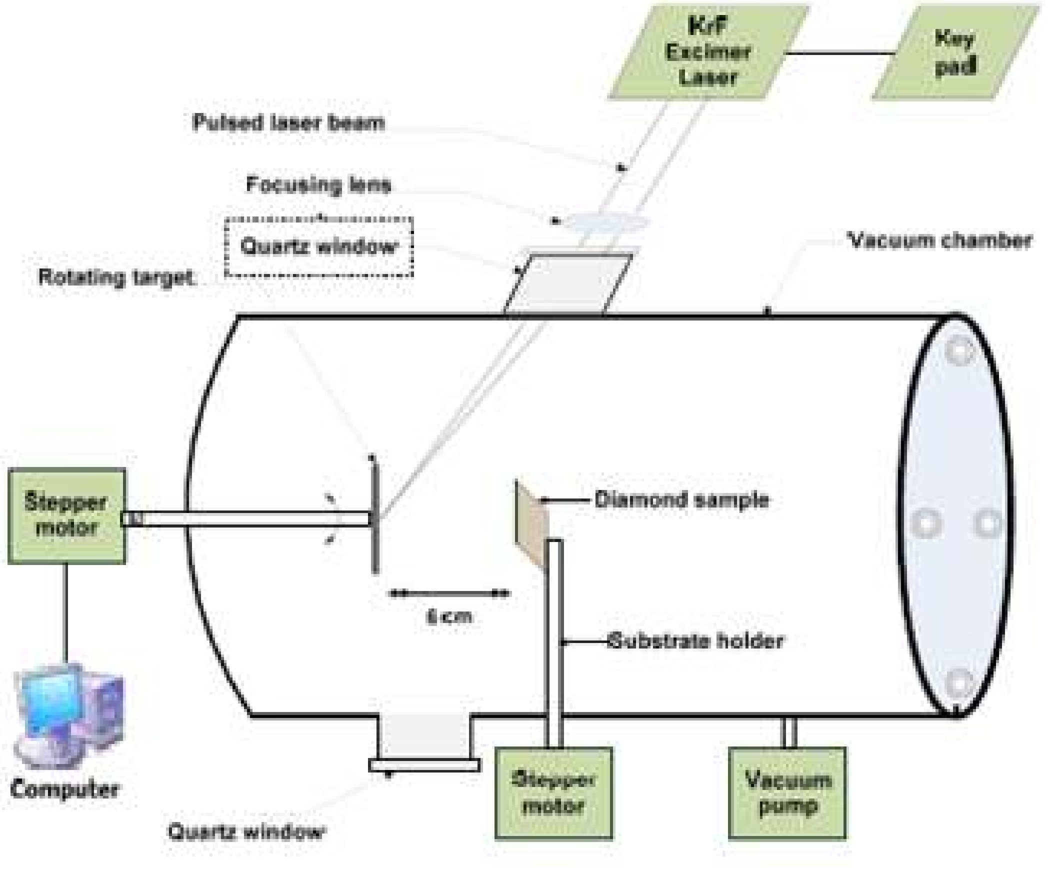


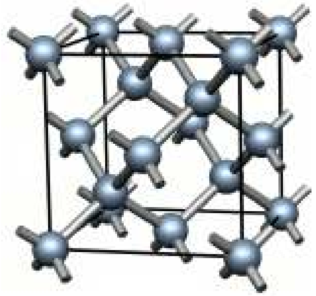
The devices show a rise and fall-off time within one sampling point which means, converted in time, ~2 seconds.

Pulsed Laser Deposition (PLD) method

Advantages of the method:

- it doesn’t originate the structural defects created by ion implantation
- better control of the contact fabrication in terms of sp2/sp3 bonding ratio which can be tuned according to the growing parameters (laser power used, atmosphere)





Source: 25 ns pulsed KrF excimer laser (Lambda-Physik LPX 210i) operating at 248 nm.

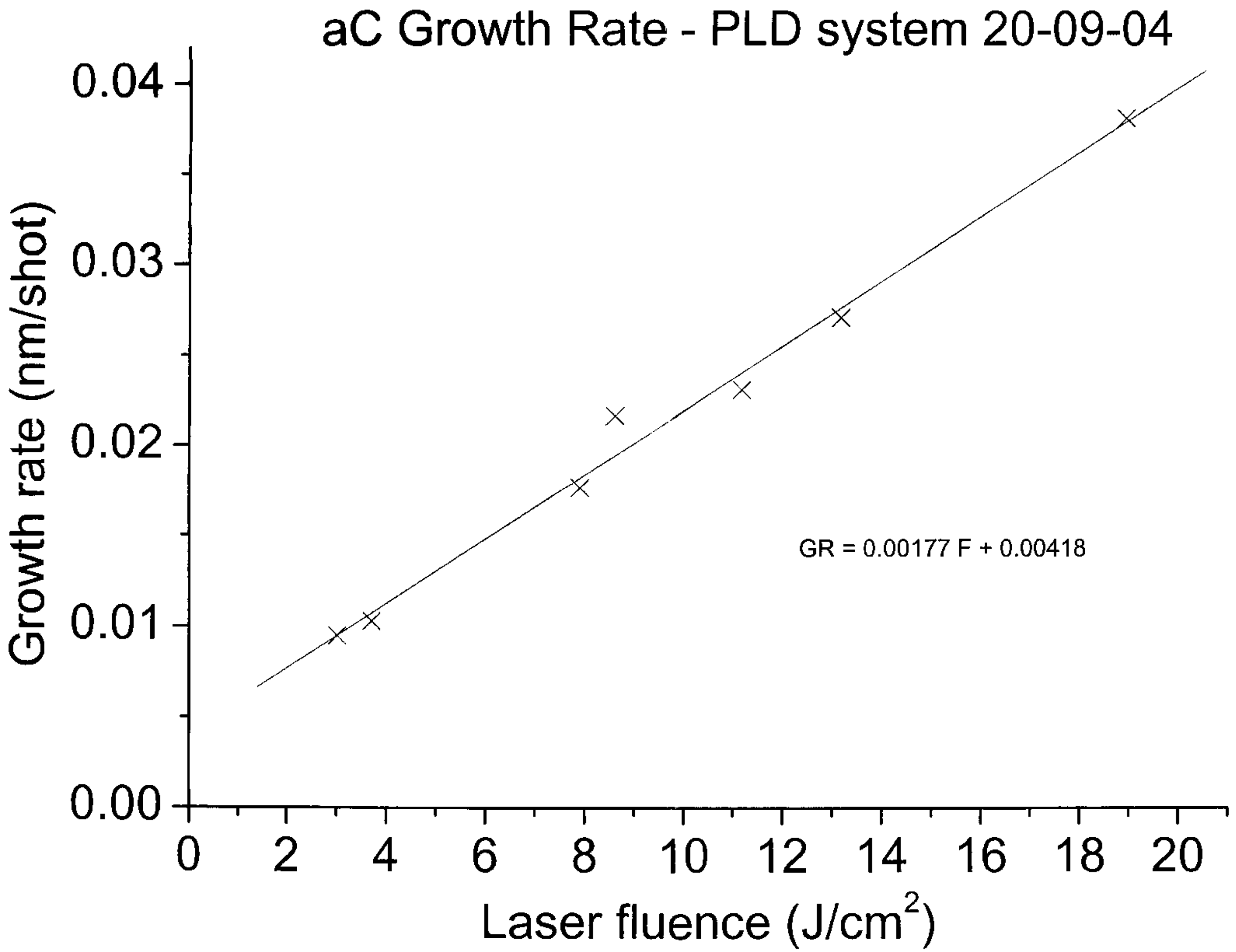
Dosimetric Properties - Summary

Dev	**Fluence (J/mm^2)**	**Bias (V)**	**I_{meas} (A)**	**SD (A)**	**I_{dark} (A)**	**I_{gen} (A)**
1	2.3	+10	$1.49 \cdot 10^{-9}$	$8.00 \cdot 10^{-12}$	$5.37 \cdot 10^{-12}$	$5 \cdot 10^{-9}$
2	2.8	+10	$1.42 \cdot 10^{-9}$	$6.57 \cdot 10^{-12}$	$5.23 \cdot 10^{-12}$	$5 \cdot 10^{-9}$
3	3.2	+10	$1.40 \cdot 10^{-9}$	$3.33 \cdot 10^{-12}$	$4.82 \cdot 10^{-12}$	$5 \cdot 10^{-9}$
4	3.6	+10	$1.51 \cdot 10^{-9}$	$5.65 \cdot 10^{-12}$	$5.70 \cdot 10^{-12}$	$5 \cdot 10^{-9}$
PTW		+100	$1.37 \cdot 10^{-9}$		$4.50 \cdot 10^{-13}$	$7 \cdot 10^{-9}$

Dev	**Gain**	**Sens. (nC/Gy)**	**Sp. Sens. (nC/Gy·mm^3)**	**Δ**	**SNR**
1	0.30	4.24	4.50	0.98	277
2	0.28	4.03	4.28	0.99	271
3	0.28	4.21	4.47	1.00	290
4	0.30	4.28	4.54	0.97	264
PTW	0.20		58.5	1.00	3000

All the fabricated devices show very similar properties

Estimation of the deposited thickness



Parameters Investigated

Dose rate dependence

$$I \quad = \quad I_0 + cD^{\Delta}$$

Photoconductive Gain

$$Gain = \frac{I_{measured}}{I_{generated}} = \frac{\tau}{T_r} \qquad I_{generated} = \frac{D\rho ev}{w}$$

Reproducibility

$$\mathrm{Reproduciblity} = \left[\left(\frac{SD}{average}\right)\times 100\right]\%$$

Sensitivity and Specific Sensitivity

Conclusions

We presented the X-ray detection characteristics of a polycrystalline electronic grade CVD diamond sensor prepared in house with four electric contacts per side in a sandwich configuration. One side had Al/Au contacts produced by sputtering deposition while the opposite side had amorphous carbon electrodes fabricated by Pulsed Laser Deposition (PLD) technique in the fluence range of 2.3 – 3.6 J/cm^2.

Results

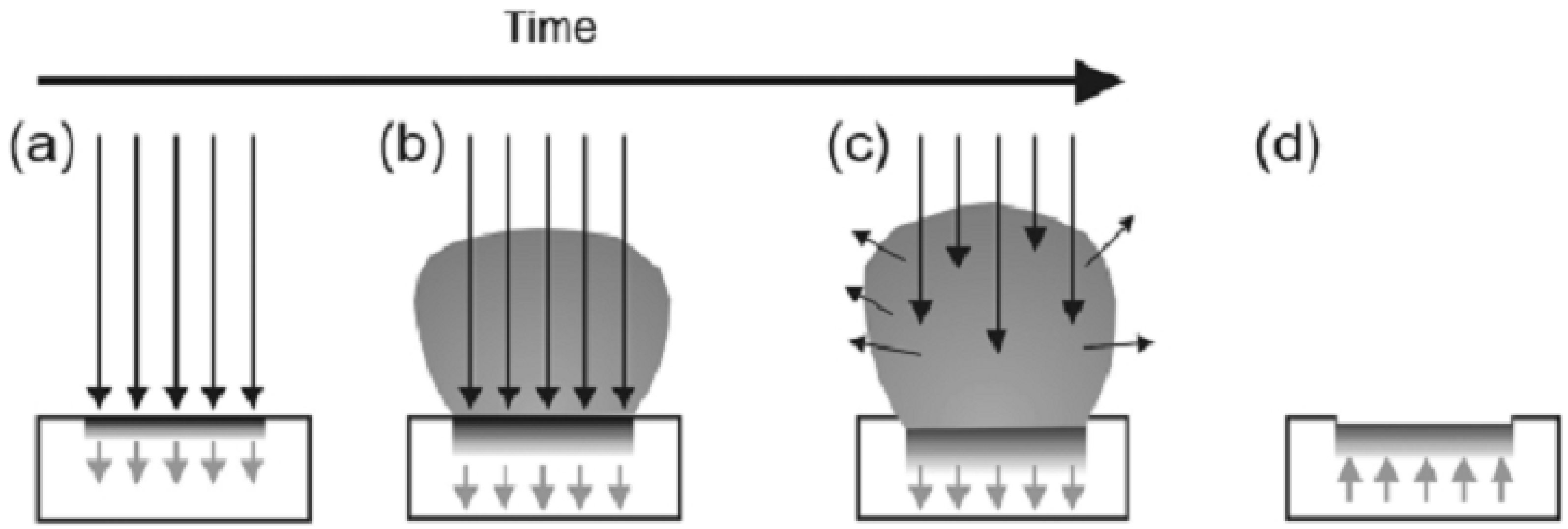
- Leakage current higher for lower values of laser flunce.

- Faster dynamic response and better stability of the signals were achieved for applied bias up to 50 V (*contact thickness too low/poor adhesion of the contacts?*)

- X-ray induced photocurrent presents a linear dependence respect to the dose rate.
- No dependence of the dosimetric properties of the device respect the different nature of the carbon electrodes (*high reproducibility of fabrication process*).

- Low laser fluence range due to the poor adhesion of the C contact on the diamond surface.

PLA event



(a) Initial absorption of laser radiation (indicated by long arrows), melting and vaporization begin (shaded area indicates melted material, short arrows indicate motion of solid-liquid interface.

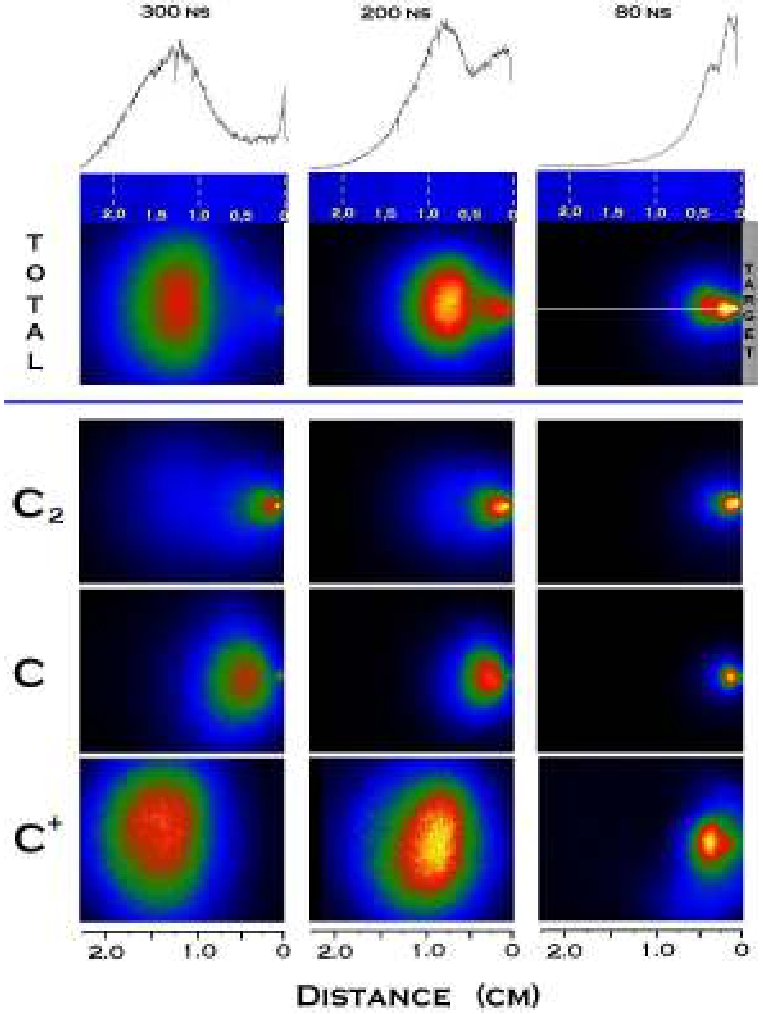
(b) Melt front propagates into the solid, vaporization continues and laser-plume interactions start to become important.

(c) Absorption of incident laser radiation by plume, and plasma formation.

(d) Melt front recedes leading to eventual re-solidification.

ns/fs ablation in vacuum

Wavelength resolved imaging



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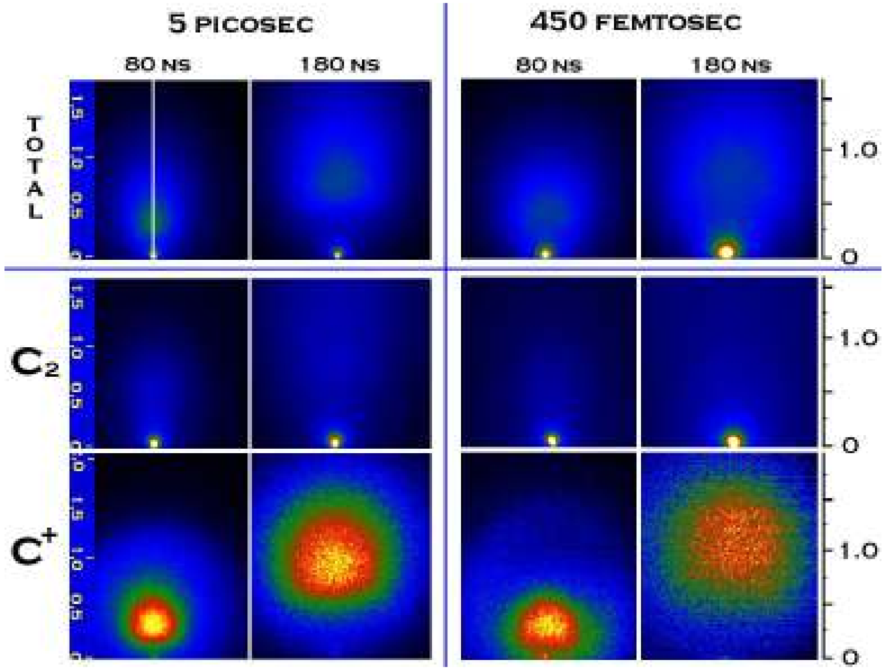

C ion velocity increases with increasing fluence.

Ions travel faster than neutrals

C_2 emission located at target