Resistant, Sensitive and Fast CVD Diamond Detectors for Intense Ionizing Radiation

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Introduction and Aim

Several medical applications rely on the interaction between high-energy radiation and human tissue. Radiotherapy, radiography, and mammography as well as high-energy physics experiments need a very precise measurement of the radiation dose imparted to the target volume. These techniques differ in the radiation energy content, but all of them require reliable, precise, and sensitive detectors to accurately calibrate the radiation sources and/or directly monitor the dose delivered to a patient.

CVD diamond is a suitable material to be used for intense x-ray and gamma dosimetry since it shows properties of tissue equivalence, radiation hardness and chemical inertness. Such characteristics imply no energy corrections respect to human tissue and advantages of long operative lifetimes.

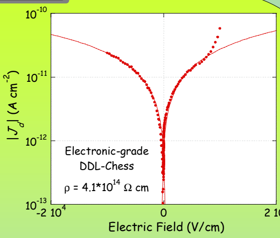
X-ray diamond dosimeters were assembled by developing injecting diamond-like-carbon/Pt/Au contacts on single-crystal high-purity diamond films with the aim to reduce space-charge effects. Resistivity in the dark of $(5.6 \pm 0.1) \times 10^{14}\ \Omega$ cm was measured as well as low density deep-states in the band-gap were evaluated from spectrally resolved photoconductivity measurements. Devices resulted to be priming-less with a linearity coefficient to x-ray (Mo-Kα) dose-rate of 1.02 ± 0.01. Transient x-ray modulated analysis allowed the determination of fast traps influence and an estimation of the dosimeters response times, very fast ($\sim 10^{-3}$ s) at high fields ($\gtrsim 3\times10^{-3}$ V/cm).

CVD Diamond pre-Characterization

Characteristics

	Normal-grade Samples	Electronic-grade Samples
Lateral size	$(4.6\pm0.1) \times (4.6\pm0.1)$ mm^2	$(4.6\pm0.1) \times (4.6\pm0.1)$ mm^2
Thickness	500 ± 50 µm	500 ± 50 µm
Crystallographic Orientation of Surfaces	{100} ± 3 deg	{100} ± 3 deg
Surface roughness	<10 nm	<5 nm
Nitrogen concentration	<1 ppm	<5 ppb
Boron concentration	<0.05 ppm	<1 ppb
RT Electrons Mobility	1714 cm^2·V^{-1}·s^{-1}	2145 ± 30 cm^2·V^{-1}·s^{-1}
RT Holes Mobility	2064 cm^2·V^{-1}·s^{-1}	2430 ± 45 cm^2·V^{-1}·s^{-1}
Electrons Saturation Velocity	0.96×10^7 cm/s	0.98×10^7 cm/s
Holes Saturation Velocity	1.41×10^7 cm/s	1.54×10^7 cm/s
Customer Cost	190 €/film	~1000 €/film

Dark I-V

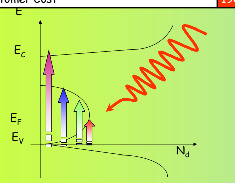


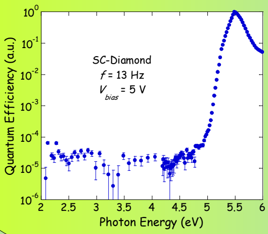
Bulk electrical resistivity equal to $(5.0\pm1.5) \times 10^{14}\ \Omega$·cm, approaching diamond intrinsic resistivity

The behavior is not perfectly symmetric: at high voltage, space-charge limited current (SCLC) conditions (I_d proportional to V_{bias}^2) can be experienced only in one voltage branch.

Non symmetric contacts?

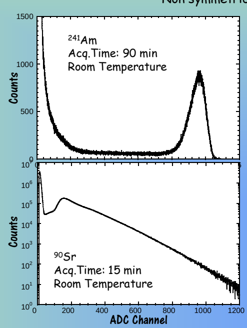
Spectral Photo-Conductivity





- A quantum efficiency value close to 100% for hv = E_G
- 5 orders of magnitude of UV (hv > E_G) - VIS discrimination
- Evidence of a "flat" defect density of states inside the band-gap
- The presence of an Urbach Tail with an Urbach Energy of (40 ± 12) meV, indicative of shallow defect states
- Surface recombination for hv > E_G due to surface absorption

Pulsed Sources



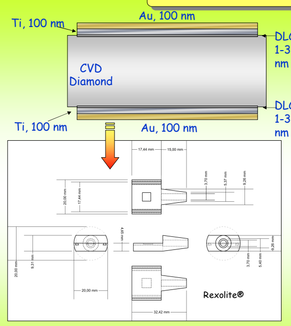
- CVD diamond is able to distinguish at room temperature pulsed radioactive sources as ^{241}Am (alpha particles) and ^{90}Sr (beta particles).

Diamond Physical Properties

- Wide band-gap semiconductor properties (5.47 eV), very low electrical conductivity.
- Excellent electrical properties (high carriers mobility and breakdown electric field).
- The most resistant solid material.
- The most thermal conductive material (4 times larger than copper and 3 times than silver).
- UV, Visible light, IR blindness (down to 225 nm).
- High electron emission capability (NEA, negative electron affinity).
- The most radiation-damage resistant solid material.
- Biocompatible and tissue-equivalent (Z=6).
- Chemical inertness.

Property	Diamond	SiC	Silicon	
Band-Gap Energy (eV)	5.47	2.36-3.26	1.12	Wide Band-Gap Semiconductor
Intrinsic Electric Resistivity (Ω·cm)	$>10^{15}$	10^9–10^{12}	3.2×10^5	Electrically Insulating & Thermally Conductive
Thermal Conductivity (W·cm^{-1}·K^{-1})	20	3.6-4.9	1.12	
Breakdown Electric Field (V·cm^{-1})	$>10^7$	4×10^6	3×10^5	Excellent electrical properties
Electron Mobility (cm^2·V^{-1}·s^{-1})	1800	500-1000	1500	
Hole Mobility (cm^2·V^{-1}·s^{-1})	1200	100-400	600	
Dielectric Constant (ε_r)	5.7	9.7	11.9	
Ionization Energy (eV)	13	8.4	3.6	3.6 and 1.5 times less sensitive than Si and SiC, respectively
Wigner Energy (eV)	43	25	13	High Radiation Damage Resistance
Degradation Dose (kGy)	100	30	1	
Atomic number (Human Tissue ~ 6.5)	6	~10	14	Tissue-equivalent behavior

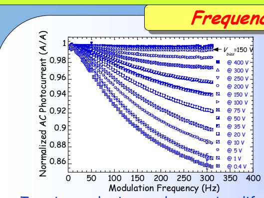
Device Fabrication

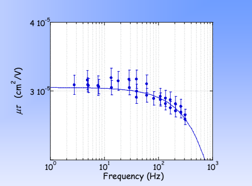


Bonding: Al-Si (99%-1%) 25 µm wires
Final encapsulation with Epotek 301 biphasic resin

Triaxial Cable:
- Length 0.1 - 6 m
- Impedance 50 Ω, Capacitance 50 pF/m

Frequency Dependence



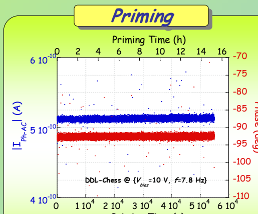


- Trapping mechanisms reduce carriers lifetime in competition with thermionic re-emission favored by bias voltage.
- "Flat curve" condition is obtained by applying voltages > 150 V (electric field > 3000 V/cm)
  - Very fast detectors (ms range or less)

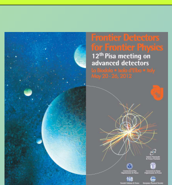
$\mu\tau$ = constant = $(3.0 \pm 0.5) \times 10^{-5}$ cm^2 V^{-1}

$\mu \approx 2.2 \times 10^3$ cm^2 V^{-1} s^{-1} ⇨ $\tau \approx 14 \pm 3$ ns

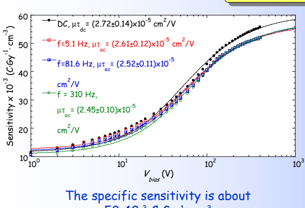
Priming



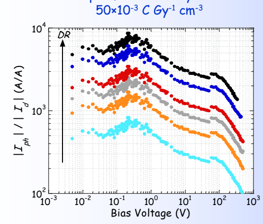
- Electronic-Grade Films do not suffer from priming! ⇨ No Deep Traps!



Dosimetric Performance

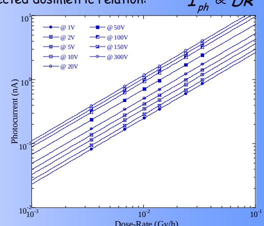


The specific sensitivity is about 50×10^{-3} C Gy^{-1} cm^{-3}

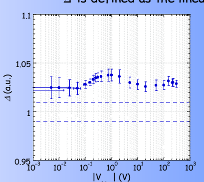


Signal to leakage ratio is in the range 10^3 - 10^4

Signal shows, as a function of radiation dose-rate, the expected dosimetric relation: $I_{ph} \propto DR^{\Delta}$



Δ is defined as the linearity coefficient.



- Electronic-Grade detectors show a slightly overlinear response to dose-rate (Δ = 1.030 ± 0.005).

Conclusions

Fast diamond dosimeters with high sensitivity, stability with time and linear response to x-ray dose-rate were developed. DC and AC lab-level x-ray techniques provide a full dosimeter characterization and results comparable to those obtained by standard radiotherapy techniques. AC x-ray photocurrent measurements allowed us to analyze the influence of shallow traps and highlight the operative conditions for obtaining a very fast response of the detectors. These results support the present maturity of diamond detectors technology in fast radiation monitoring applications.

For details, see also D.M. Trucchi et al., *IEEE Electron Device Letters* 33 (2012) 615.