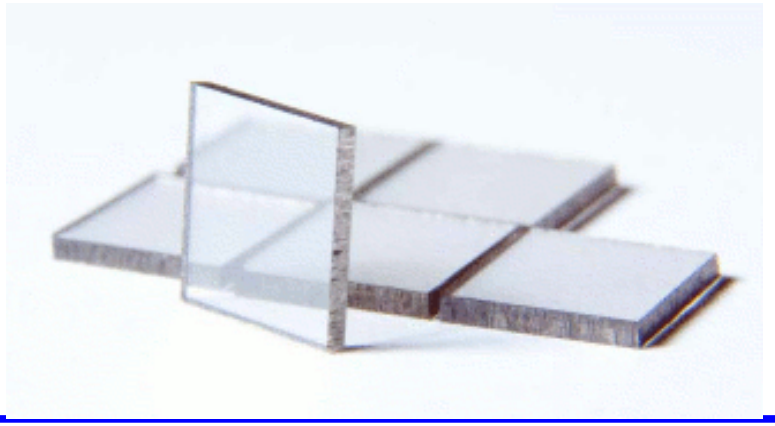
DIAMOND DETECTORS LIMITED

Influence of Electrical Contacts on the Performance of Diamond Radiation Detectors

Arnaldo Galbiati



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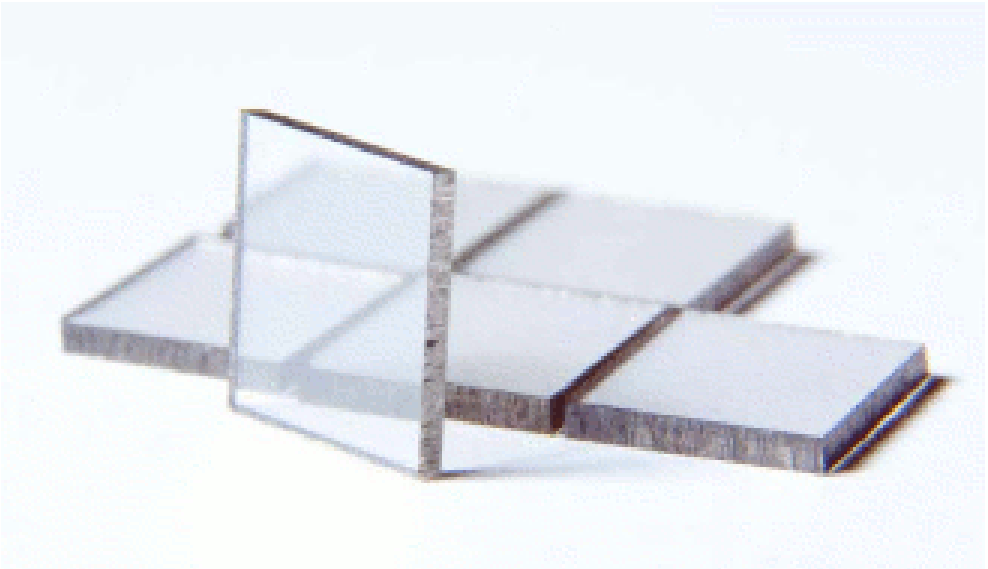
Research, Development and Production:

- **High Energy Physics**
- **Nuclear and Environmental Monitoring**
- **Radiotherapy Dosimetry**
- **Deep UV Detection**
- **Space and Astronomy**



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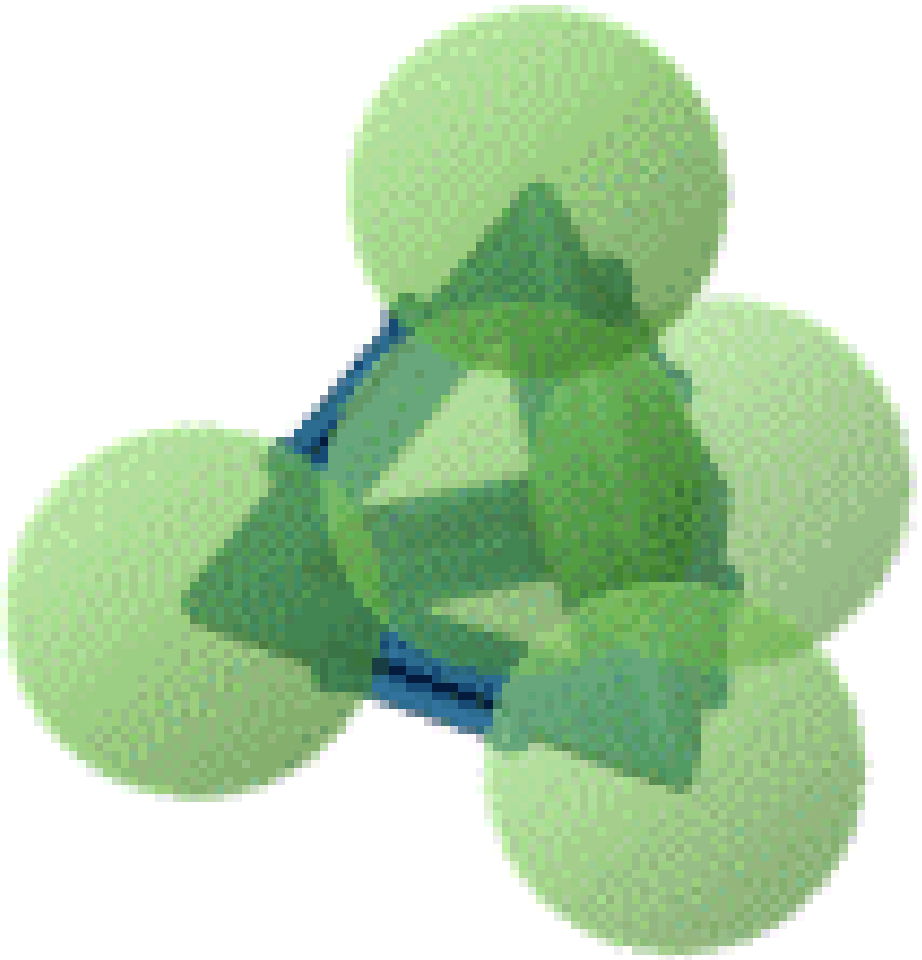
Intrinsic Material Properties

	Si	4H-SiC	GaN	Natural Diamond	CVD Diamond	Potential device application benefit
Bandgap (eV)	1.1	3.2	3.44	5.47	5.47	High temperature
Breakdown field ($MVcm^{-1}$)	0.3	3	5	10	10	High voltage
Electron saturation velocity ($x10^7$ cm s^{-1})	0.86	3	2.5	2	2	High frequency
Hole saturation velocity ($x10^7$ cm s^{-1})	n/a	n/a	n/a	0.8	0.8	
Electron mobility ($cm^2 V^{-1} s^{-1}$)	1450	900	440	200–2800	4500	
Hole mobility ($cm^2 V^{-1} s^{-1}$)	480	120	200	1800–2100	3800	
Thermal conductivity ($Wcm^{-1} K^{-1}$)	1.5	5	1.3	22	24	High power
Johnson's figure of merit	1	410	280	8200	8200	Power-frequency product
Keyes' figure of merit	1	5.1	1.8	32	32	Transistor behavior thermal limit
Baliga's figure of merit	1	290	910	882	17200	Unipolar HF device performance

Isberg, J., *et al.*, *Science* (2002) **297**, 1670

Diamond tetrahedron



(from ww.pdymorf.net/matter14.htm)

Poly CVD Cross Section

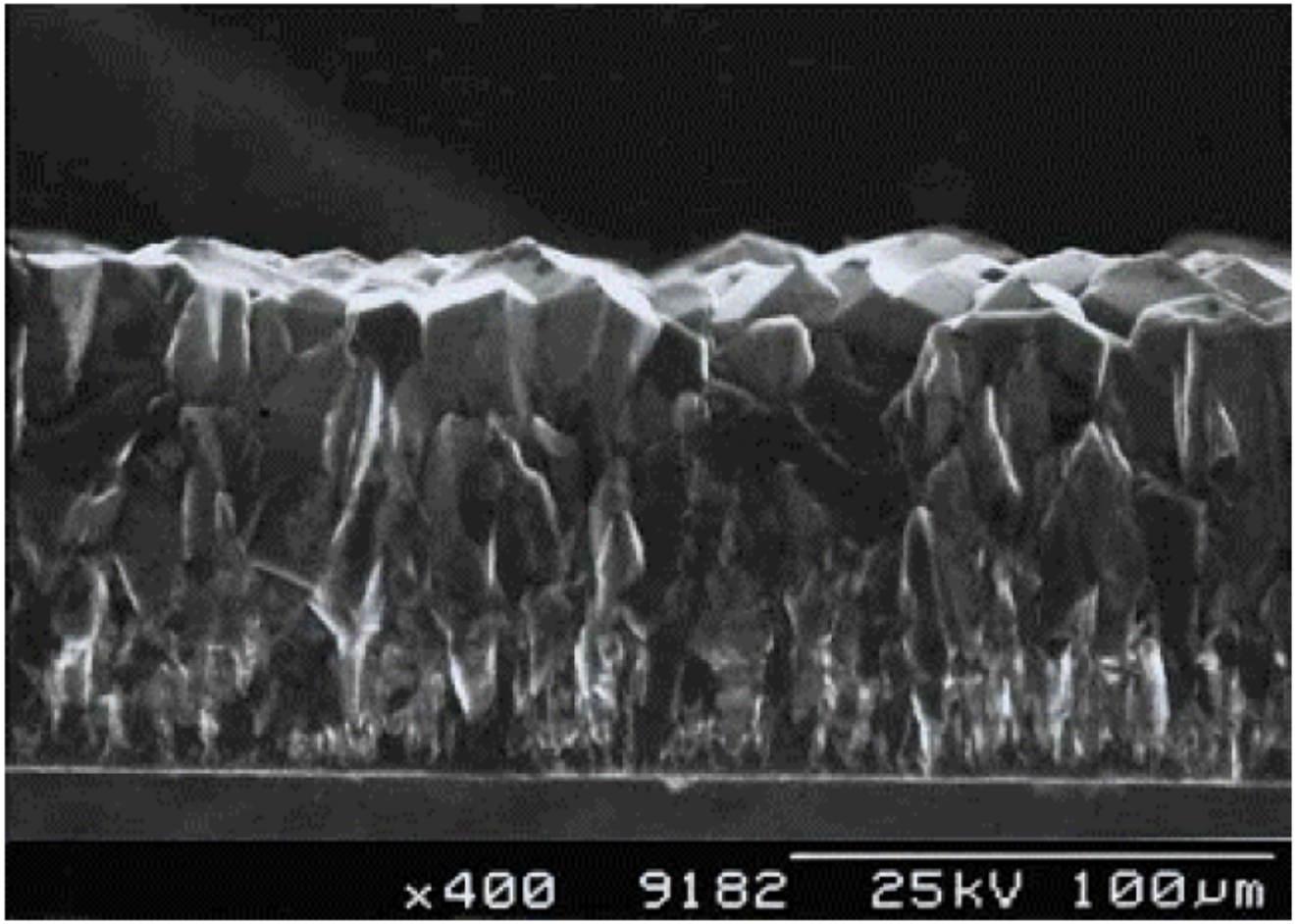


Figure 2-11: Cross-section of a 100 µm-thick CVD diamond film grown by DC arc jet. The columnar nature of the growth is clearly evident, as is the increase in film quality and grain size with growth time. (from http://www.chm.bris.ac.uk/pt/diamond/semflat.htm)

First Radiation Detectors (1945) From Natural Diamond

At that time counting properties were found to be uncontrollable, depending upon the crystal and the type of radiation.

•Furthermore, charge polarization occurred, leading to a progressive reduction in both counting rate and pulse amplitude as a function of the time of irradiation.

•P.J. VAN HEERDEN, Thesis Utrecht, 1945.
•R. HOFSTADTER., Phys. Rev. 73 (1948) 631.

•Since 1970, the attractive properties of diamond for radiation detection were demonstrated by KOZLOV et al. from mono-crystalline diamond stones of extremely high electronic quality.

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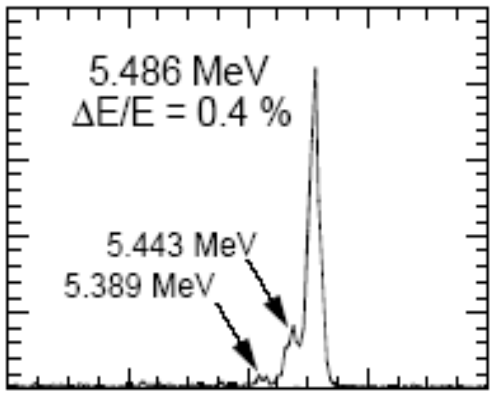
Alpha Particle Detection History in Diamond



CVD diamond single crystal

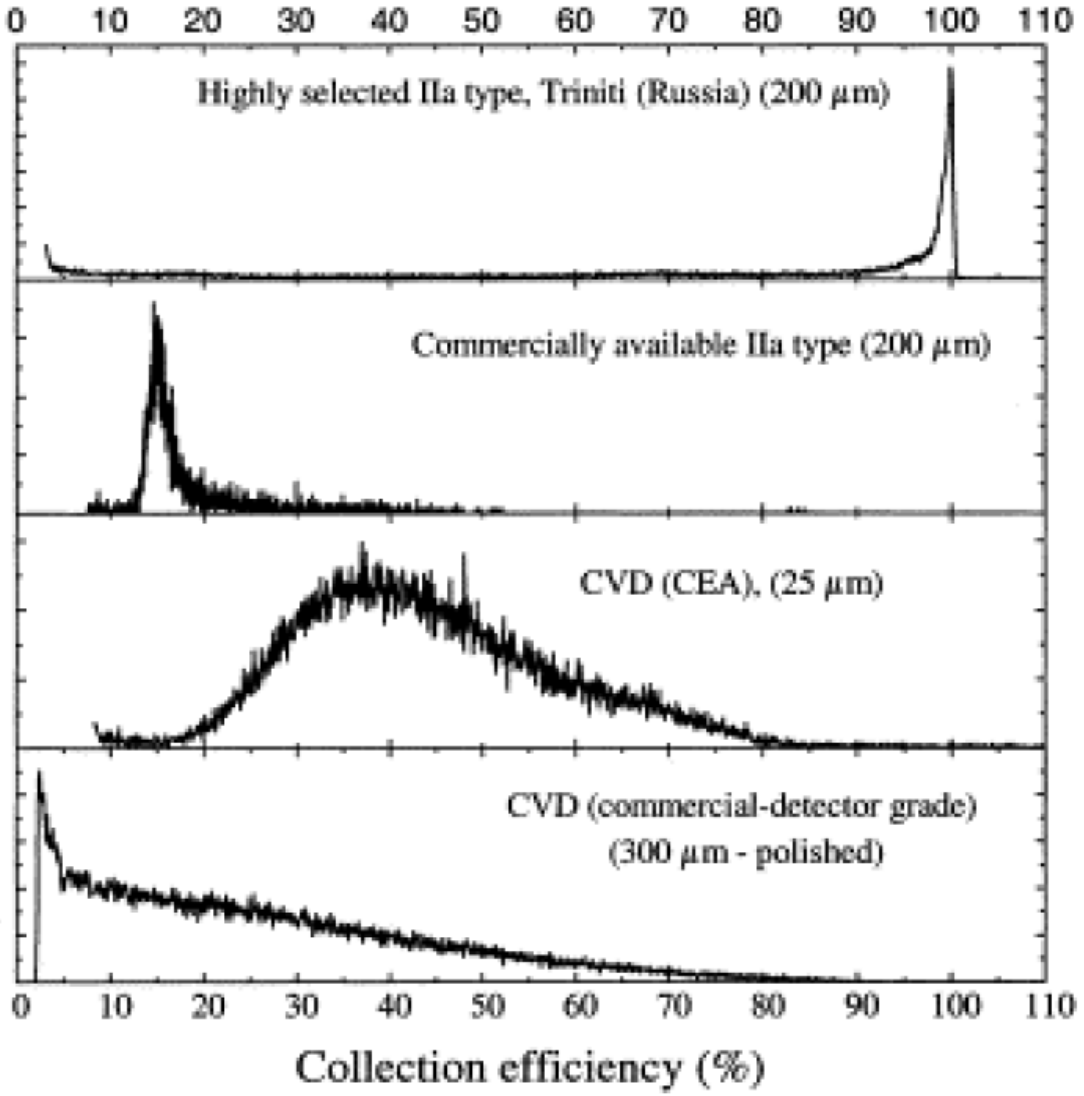


Figure 2-24: ^{241}Am detection spectra recorded on 4 grades of natural and CVD diamond [Ber01]

Bergonzo et al., *Diamond and Related Materials,* Volume 10, Issues 3-7, March-July (2001), 631-638

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Device Fabrication Issues

1. Mechanical Adhesion of the Contact
   (the flatter the surface -> less adhesion)
2. Good Injecting Contacts, Polarization Free
   (high work function metals, B doped layer)
3. Stability, Reproducibility, Durability

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Difficulty in mechanical adhesion

Property	Diamond	Silicon
Atomic number	6	14
Atomic weight	12,01	28,09
Density $\rho_m\ (g\,cm^{-3})$	3,52	2,33
N. Atoms $(x10^{22} cm^{-3})$	17,7	4,96
Atomic Distance $(\AA)$	1,54	2,35
Fusion $(°C)$	4100	1420
Work function $\Phi(eV)$	4,81	4,58
bandGap (eV)	5,5	1,12
Electrical Breakdown (V/cm)	10^7	$3\ 10^5$
Resistività (Ω/cm)	$>10^{11}$	$2,3\ 10^5$
Densità intrinseca portatori (cm^{-3})	$<10^3$	$1,5\ 10^{10}$
Mobilità degli elettroni $(cm^2V^{-1}s^{-1})$	1800-**2200**	1350
Mobilità delle lacune $(cm^2V^{-1}s^{-1})$	1200	480
Costante dielettrica	5,7	11,9
Energia di coesione atomica $(eV$/atomo$)$	7,37	4,63
Conducibilità termica $(Wm^{-1}K^{-1})$	1000-2000	150
Energia di creazione di una coppia e-h (eV)	13	3,6

Difficulty in Making Ohmic Contact

Low Leakage current- No Cooling Needed

High Radiation Hardness

Device Fabrication

- One of the problems encountered when manufacturing semiconductor devices in diamond is the fabrication of low resistance ohmic contacts.
- Historically, there have been three main approaches to solve this problem and lower the resistivity of the contact:

1. Damaging the diamond surface in order to disrupt the sp^3 bonding.

2. Using carbide forming metals like titanium or chromium, that create an hybrid metal-diamond interface material.

3. Doping of diamond during growth or using ion implantation.

Polarization free contacts

•It has been observed that polarization phenomena occur when electric currents pass through an insulator crystals.

•The bandgap of diamond being large, and the resistivity extremely high the same situation occurs here.

• **If the electrical contact is not able to extract and inject electrons fast enough**, then the neutrality of the crystal after the passage of ionizing nuclear radiations is not restored in the time interval between two consecutive events.

•As a result, charge accumulation occurs within the crystal. Immobile carriers establish an electric field which acts in a direction opposite to the applied field produced by the external bias voltage V.

PREPARATION AND CHARACTERISTICS OF NATURAL DIAMOND NUCLEAR RADIATION DETECTORS

S.F. KOZLOV

CONTACTS USED ON POLARIZATION FREE DIAMOND DETECTORS		
INJECTING		BLOCKING
HOLES	ELECTRONS	
Ag, Au, Pt – painting, followed by heating in air to 500–700°C for 2–3 hours. – electroless, followed by heating in air 500–700°C for 10 min.		Au, Ag, Pt – vacuum deposition by evaporation sometimes the surface is graphtized by heating to 1000–1300°C und. reduced air pressure (0.1 torr).
C – aquadag, followed by heating in vacuum to 500–700°C for 2–3 h. – heating to 1000–1300°C under 0.1 torr air pressure for 30 min. (graphitization)	C as for hole injection	
Al, B ion implantation : dose below 10E15 cm E-2, annealing in vacuum 800–1200°C, energy impl. 40–100 keV.	P, Li, C ion implantation	

IEEE Transactions on Nuclear Science, Vol.NS-22, February 1975

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Influence of Grain Boundaries on the Performance of Diamond Detectors

Arnaldo Galbiati

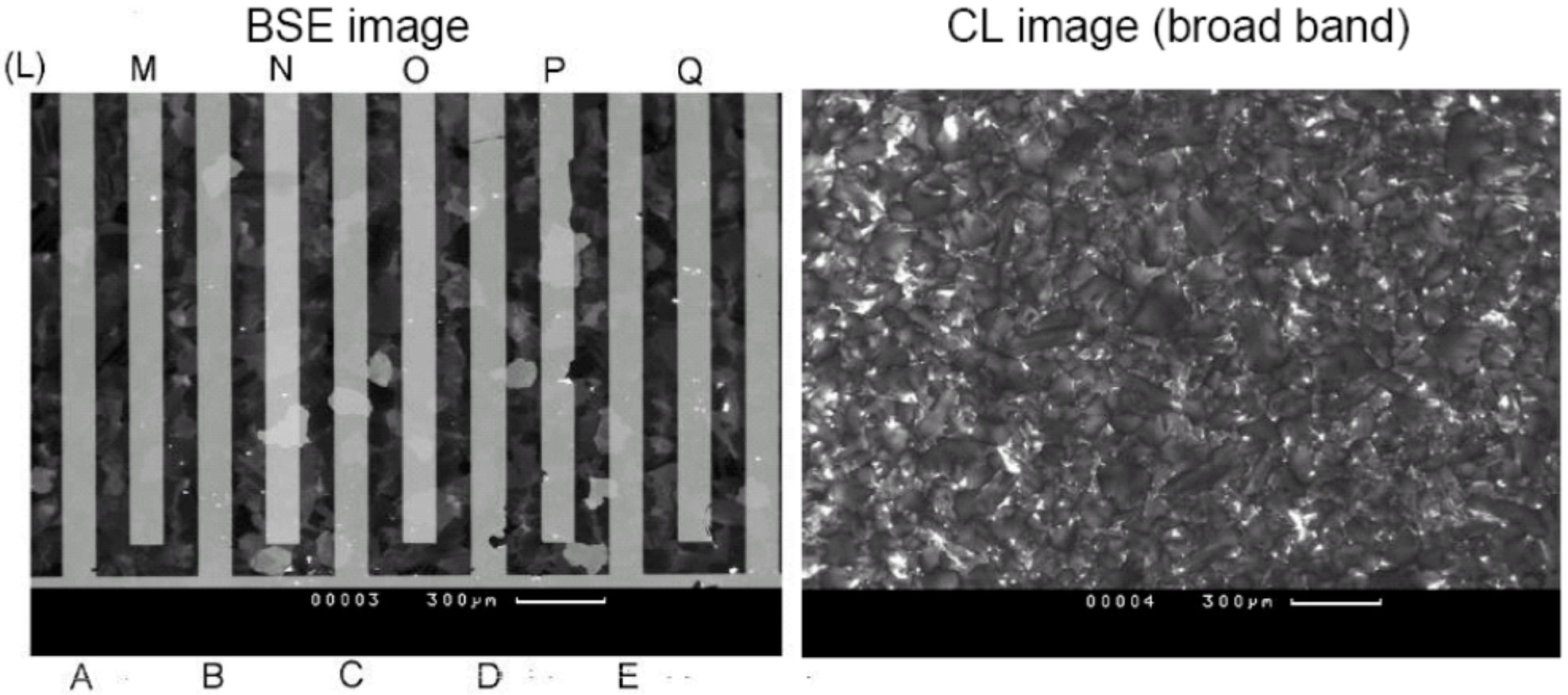

Figure 5-11: Comparison between BSE and CL image of the inter-digitated diamond sensor DF3 fabricated from high quality diamond film where the average crystallite dimension is approximately 100 µm. The image was taken of the growth surface of the film, which was polished. The device has a 100 µm inter-electrode gap and a 100 µm electrode width.

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Poly CVD Cross Section with Interdigitated Contacts

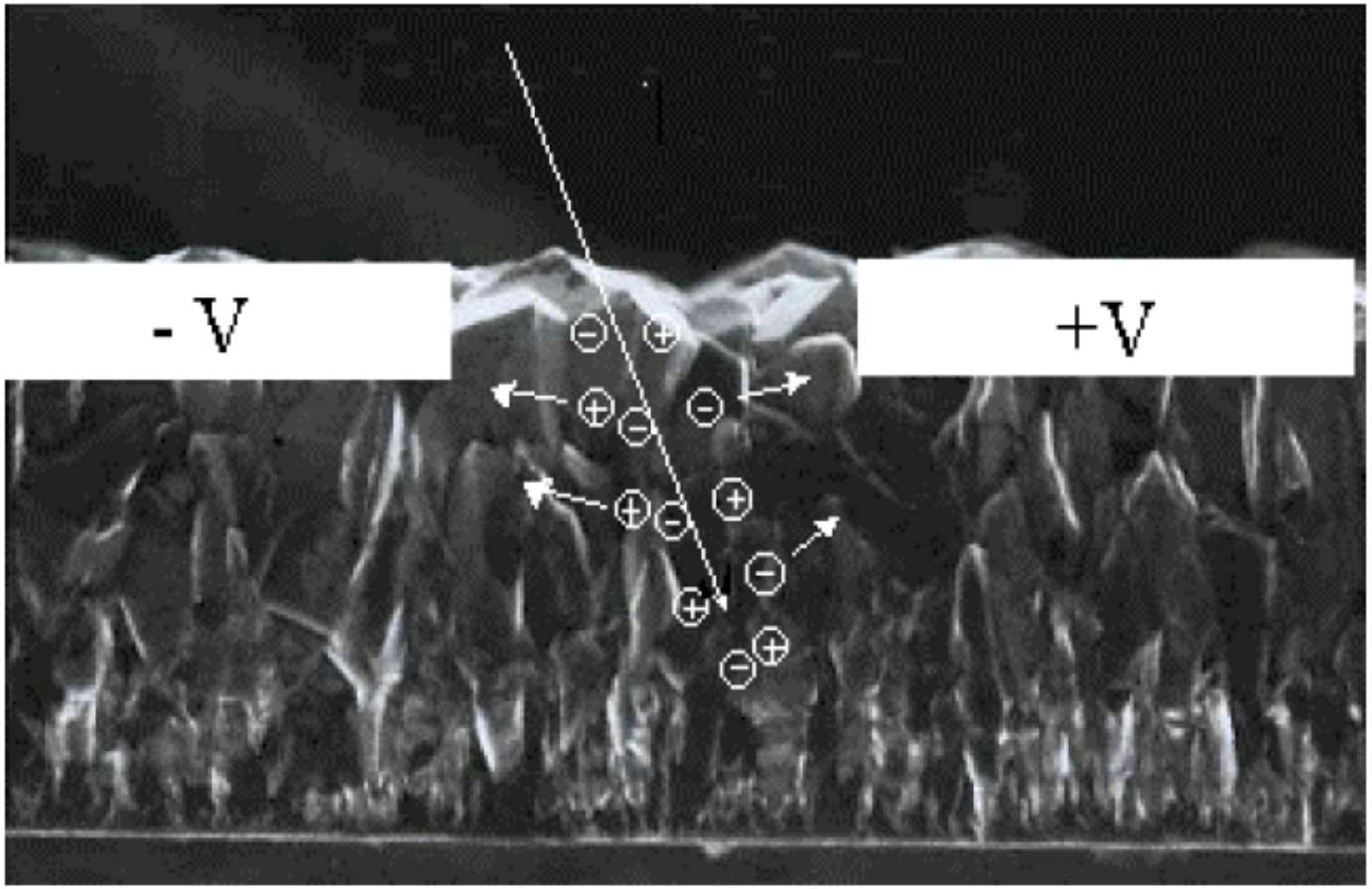

Figure 2-25 Diagram of lateral charge drift, typical of a coplanar detector with inter-digitated electrodes.

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Calculated Electric Field Profile

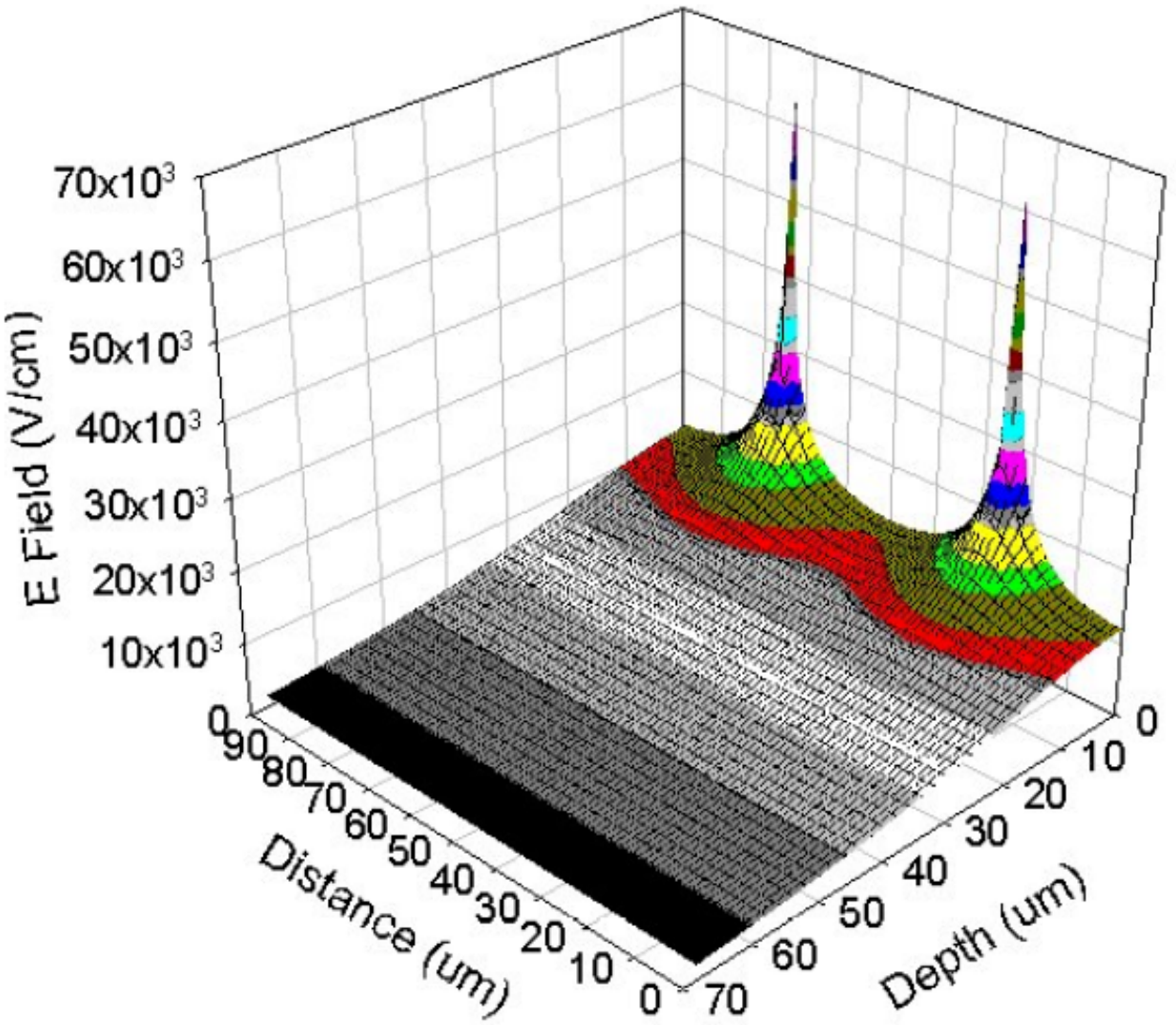

Figure 2-26. Calculated electric field profiles; 100 um pitch, 50 um gap [Sel01].

Sellin et al, *IEEE Transactions in Nuclear Science*, vol 48/6 (2001)

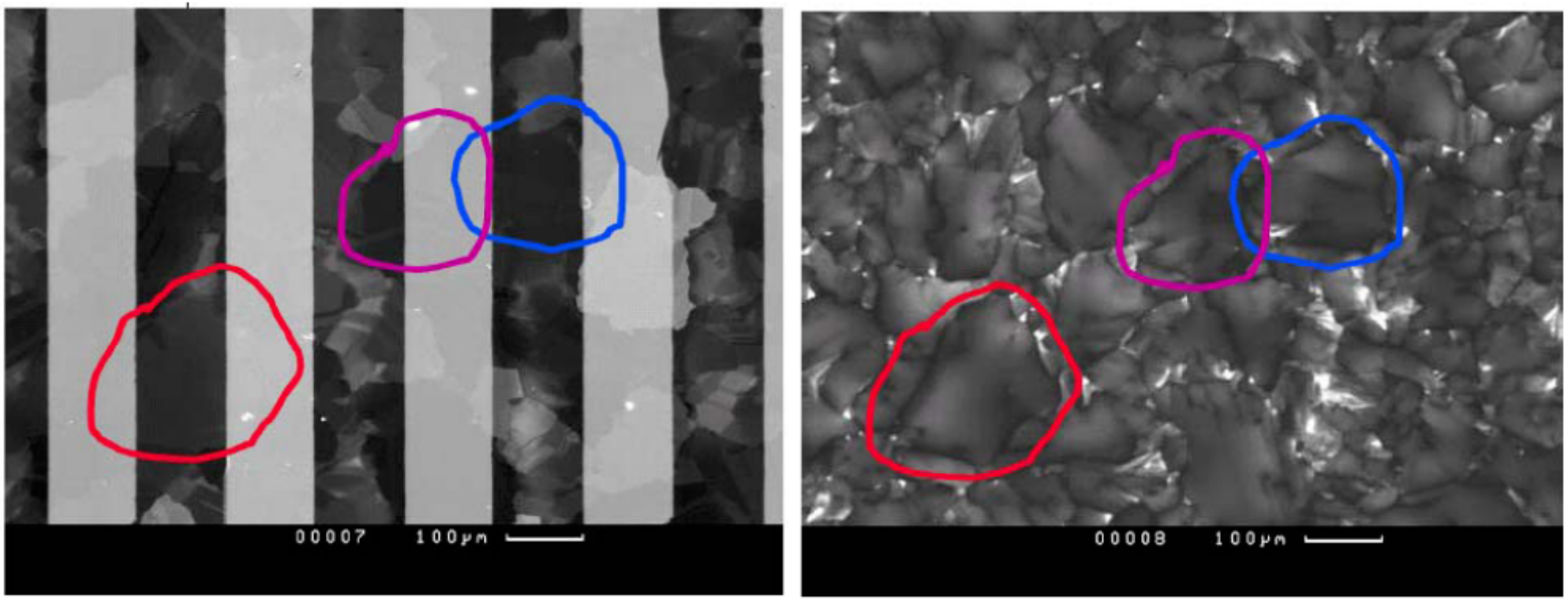

Figure 5-12: Comparison between cathodoluminescence and BSE image of regions of high quality diamond material (detector DF3). Three large crystallites are indicated by the boxed regions.

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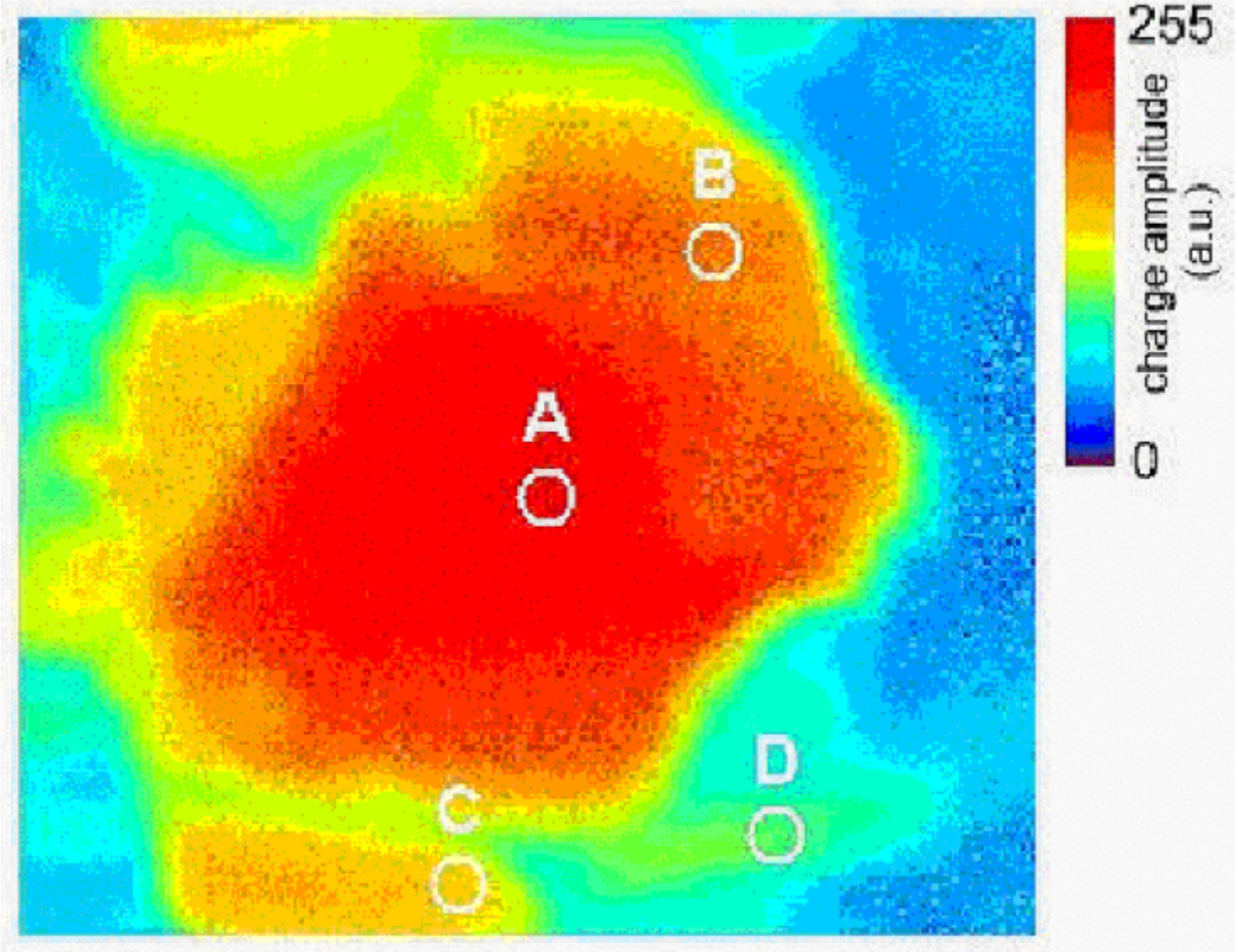

Figure 5-18: IBIC image of one of the largest crystallites identified in the device DF3

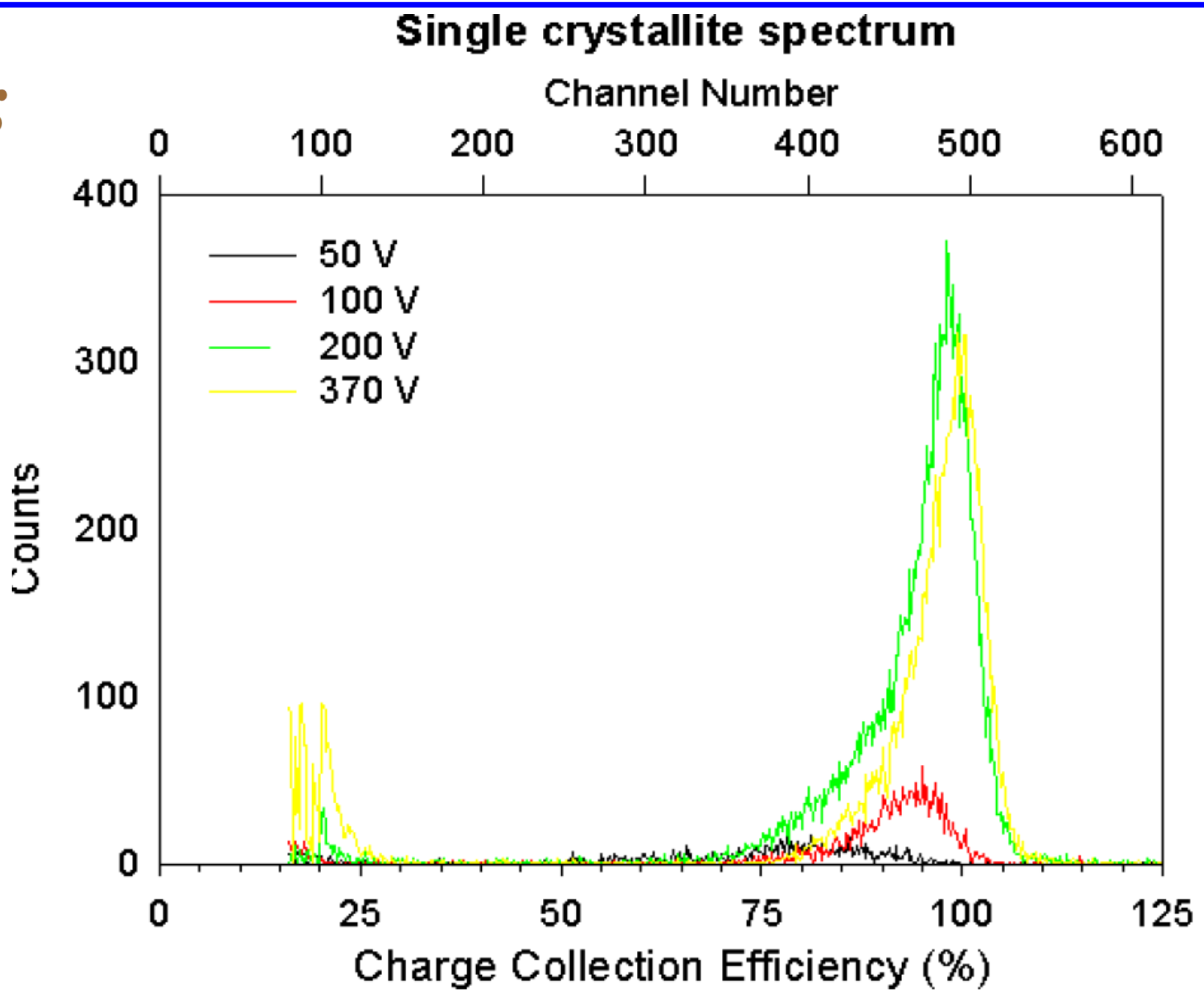

Figure 5-17: single crystallite spectrum, detector DF3.

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Ion Beam Induced Charge (IBIC) Single Crystallite Spectrum

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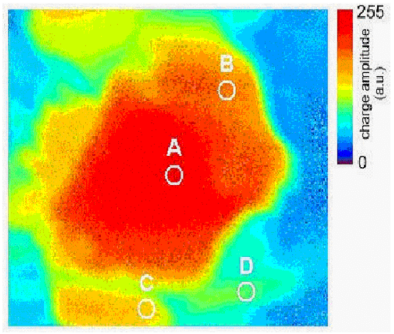

Figure 5-18: IBIC image of one of the largest crystallites identified in the device DF3

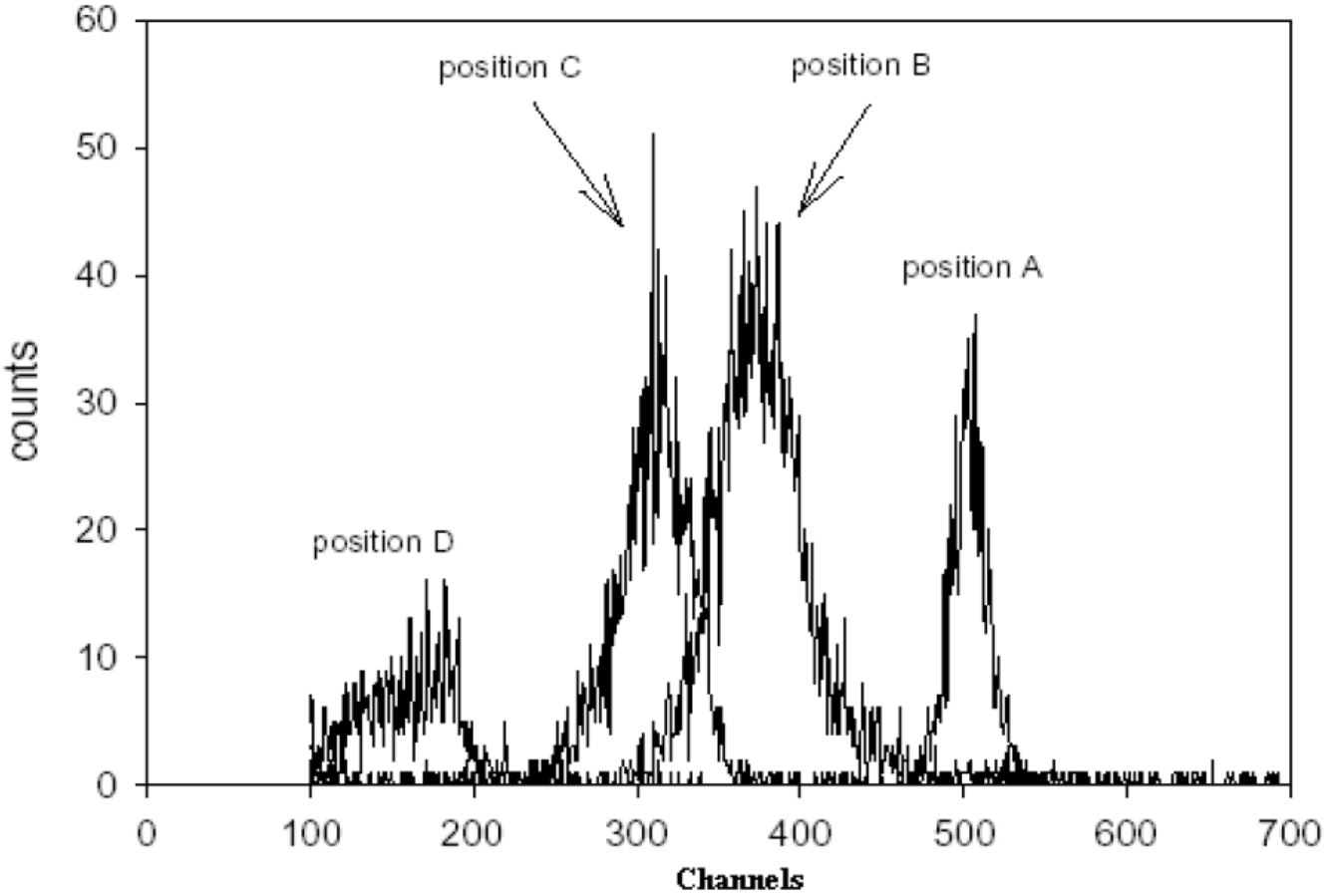

Figure 5-20: pulse height spectra extracted from four regions in the crystallite, corresponding to (A) an area of maximum charge signal in the centre of the crystallite, (B) an area towards the edge of the crystallite, (C) and (D) areas outside the crystallite, as indicated in Figure 1.

1 µm diameter focussed beam of alpha particles

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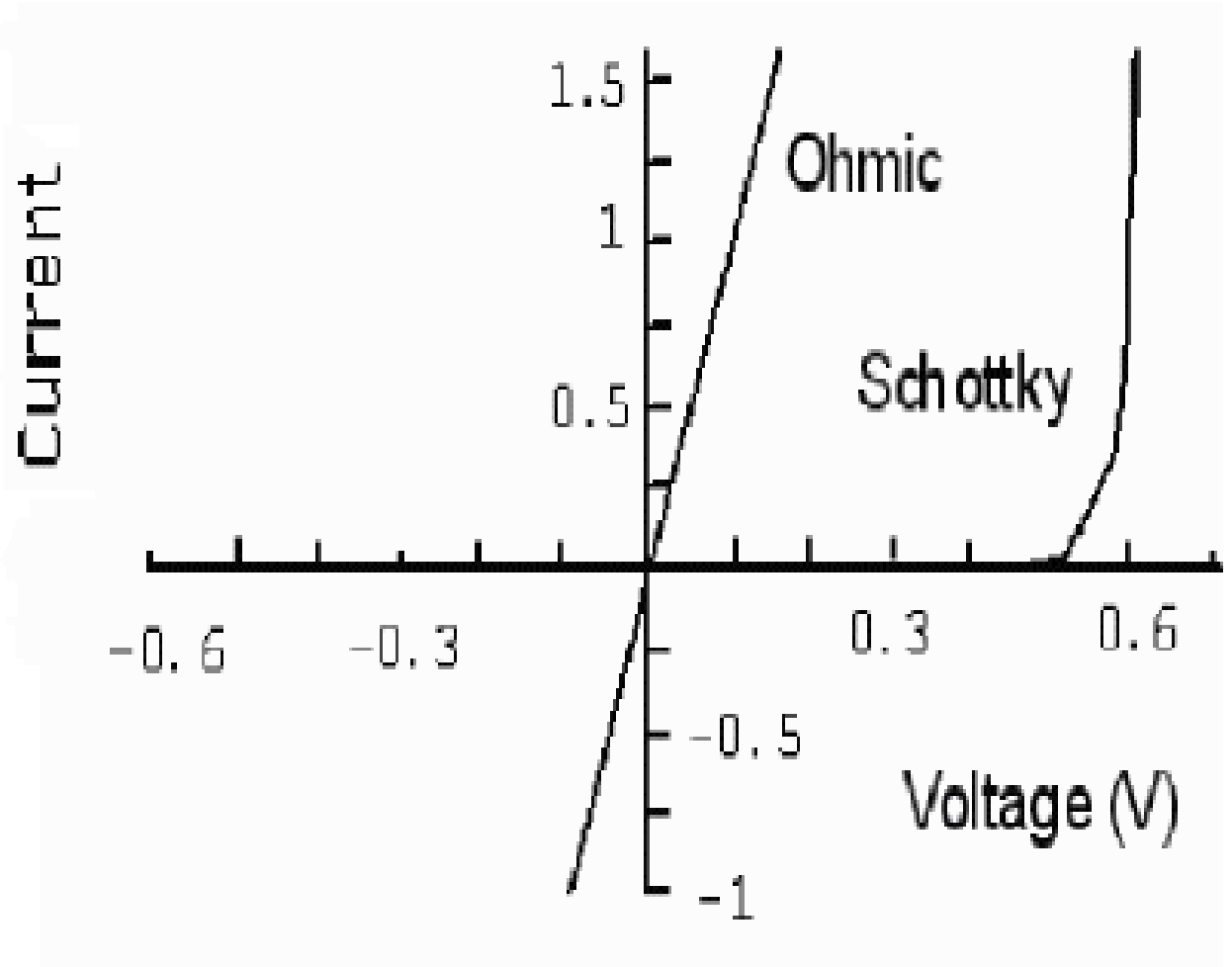
DIAMOND DETECTORS LIMITED

Influence of Metal-Diamond Interface on the Performance of Diamond Detectors

Arnaldo Galbiati



The RC time constant associated with contact resistance can limit the frequency response of devices. The establishment of a contact fabrication methodology is a critical part of the technological development of any new semiconductor. Electromigration and delamination at contacts are also a limitation on the lifetime of electronic devices.

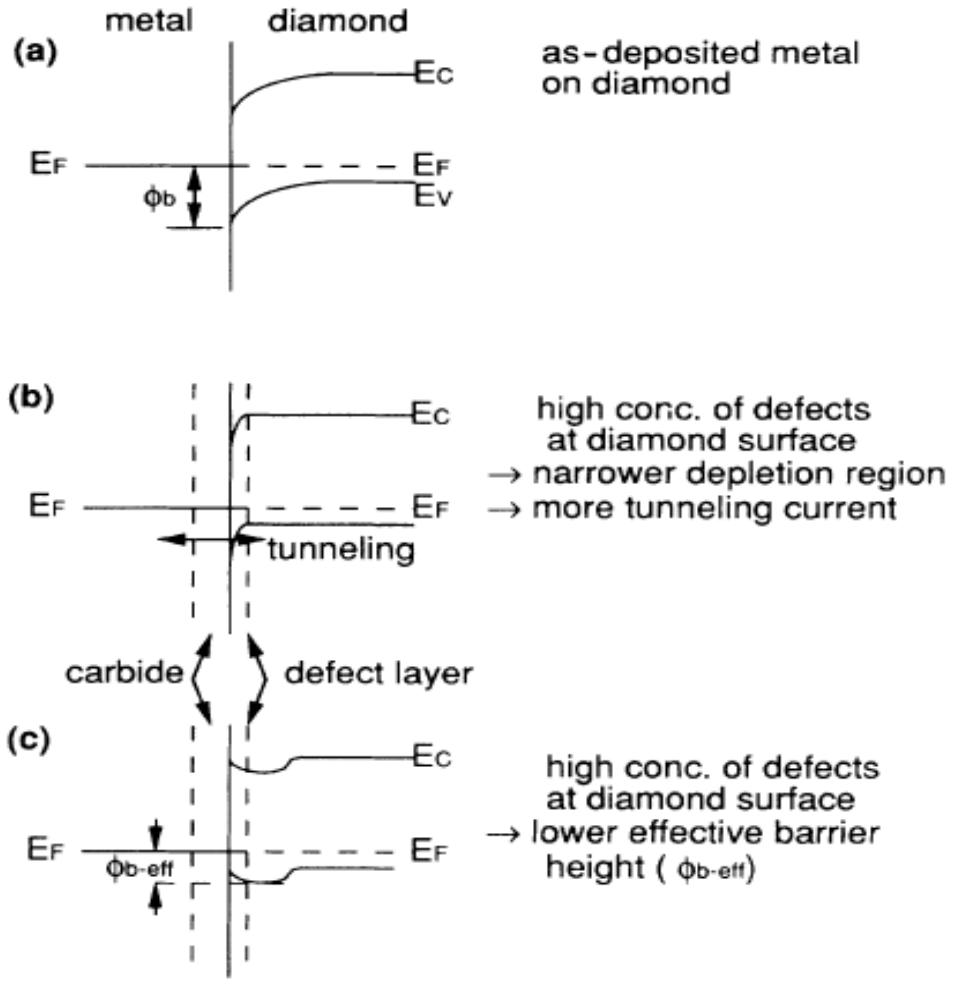
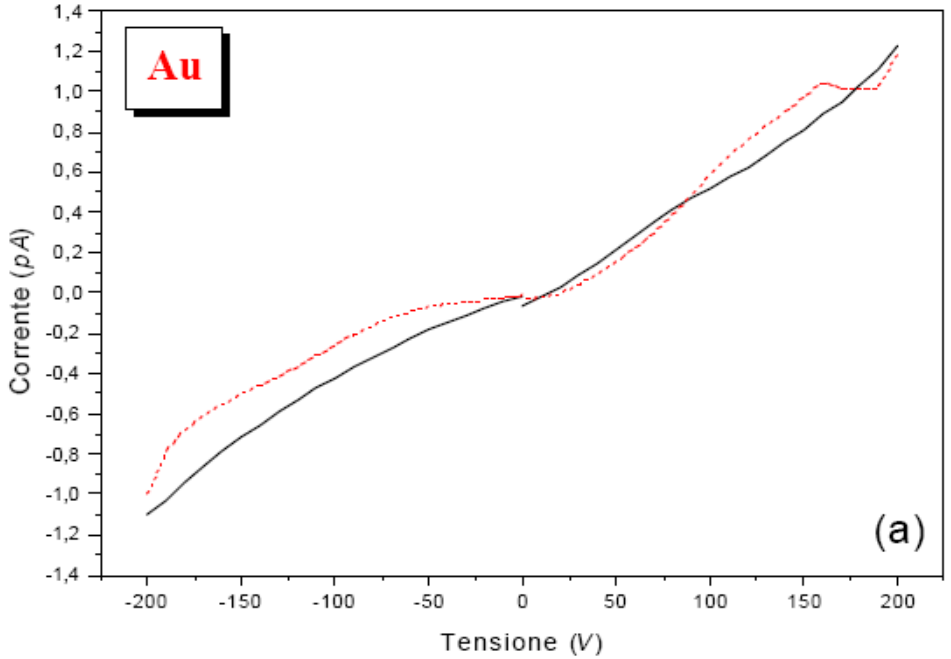
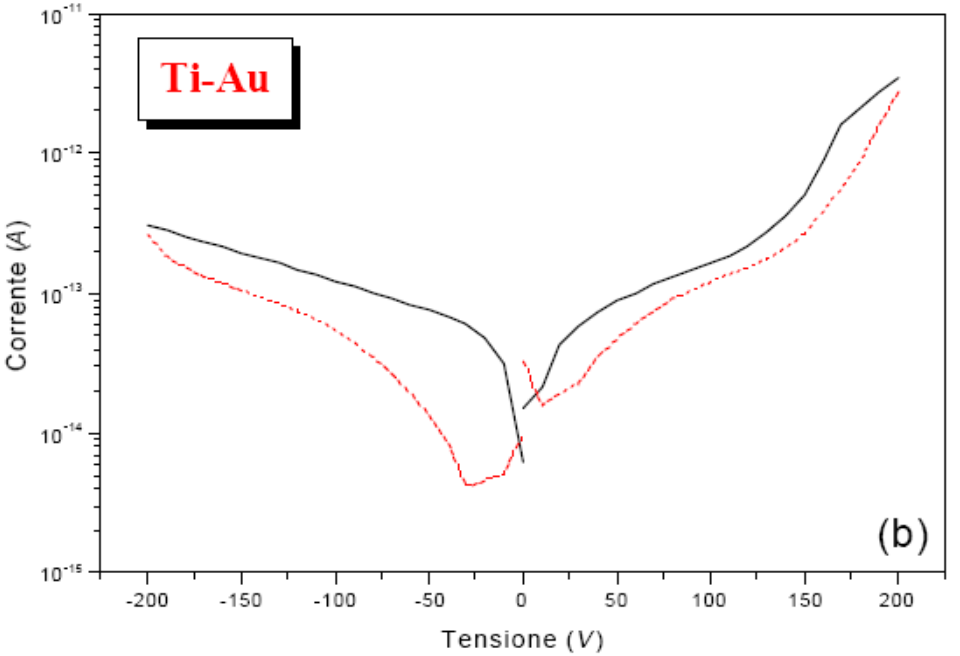
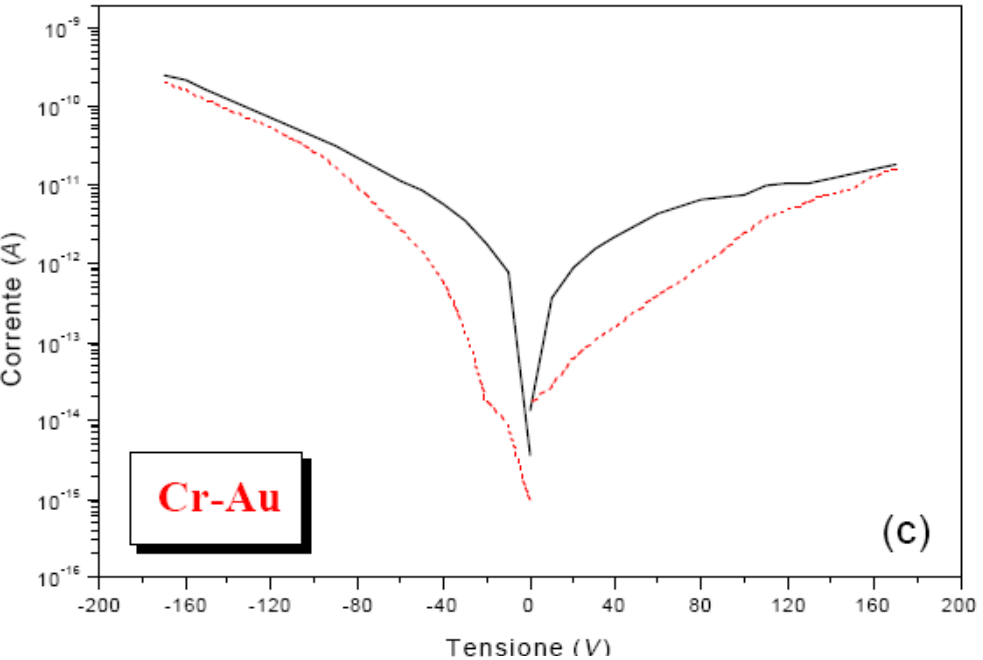


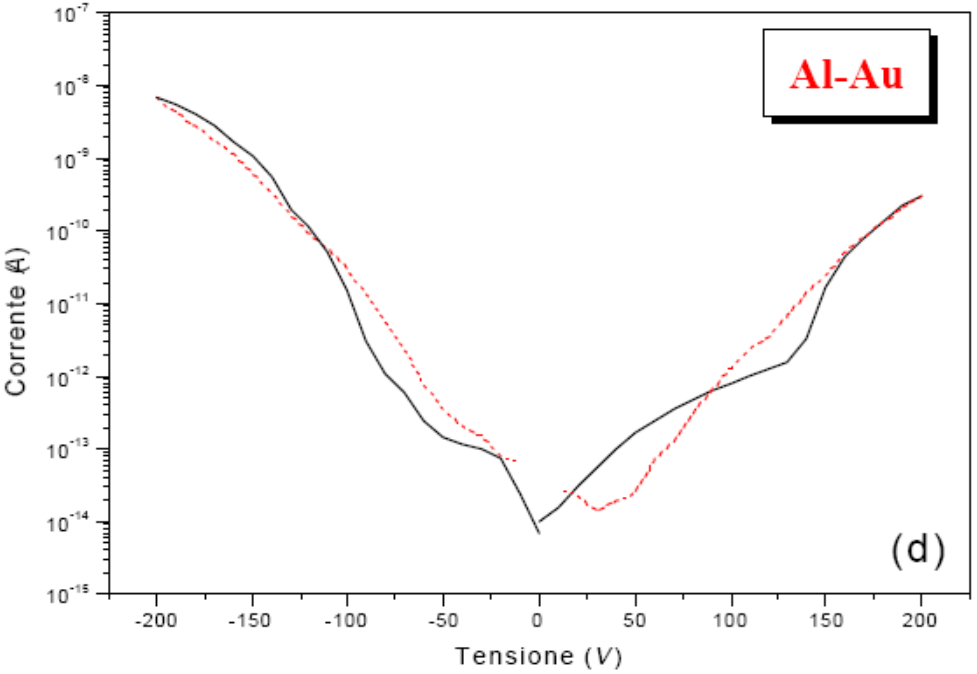
FIG. 7. Interface band diagrams of titanium on diamond; (a) as-deposited titanium on diamond, (b) high concentration of electrically active defects, which are created via the formation of a carbide and/or ion bombardment, reduces the depletion width and increases the tunneling current, (c) the electrically active defects created as in (b) decrease the effective barrier height.

Influence of metal–diamond interfaces on the response of UV photoconductors

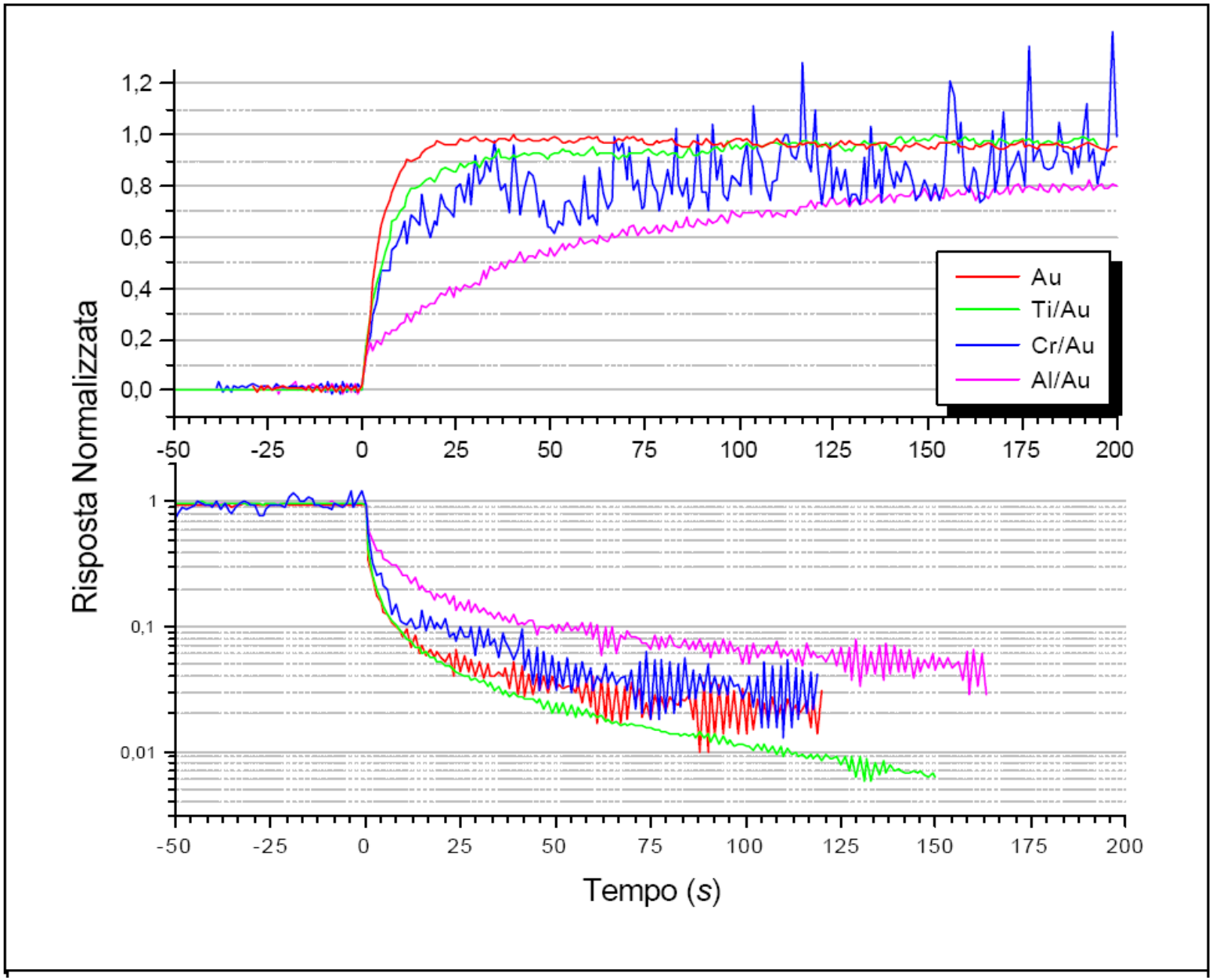








Influence of metal–diamond interfaces on the response of UV photoconductors



Cr 4.5 eV
Ti 4.3 eV
Al 4.1 eV

Au 5.1 eV

Diamond 4.8-5.8 eV

R. Di Benedetto et al. / Diamond and Related Materials 10 (2001) 698–705

Diamond Work Function

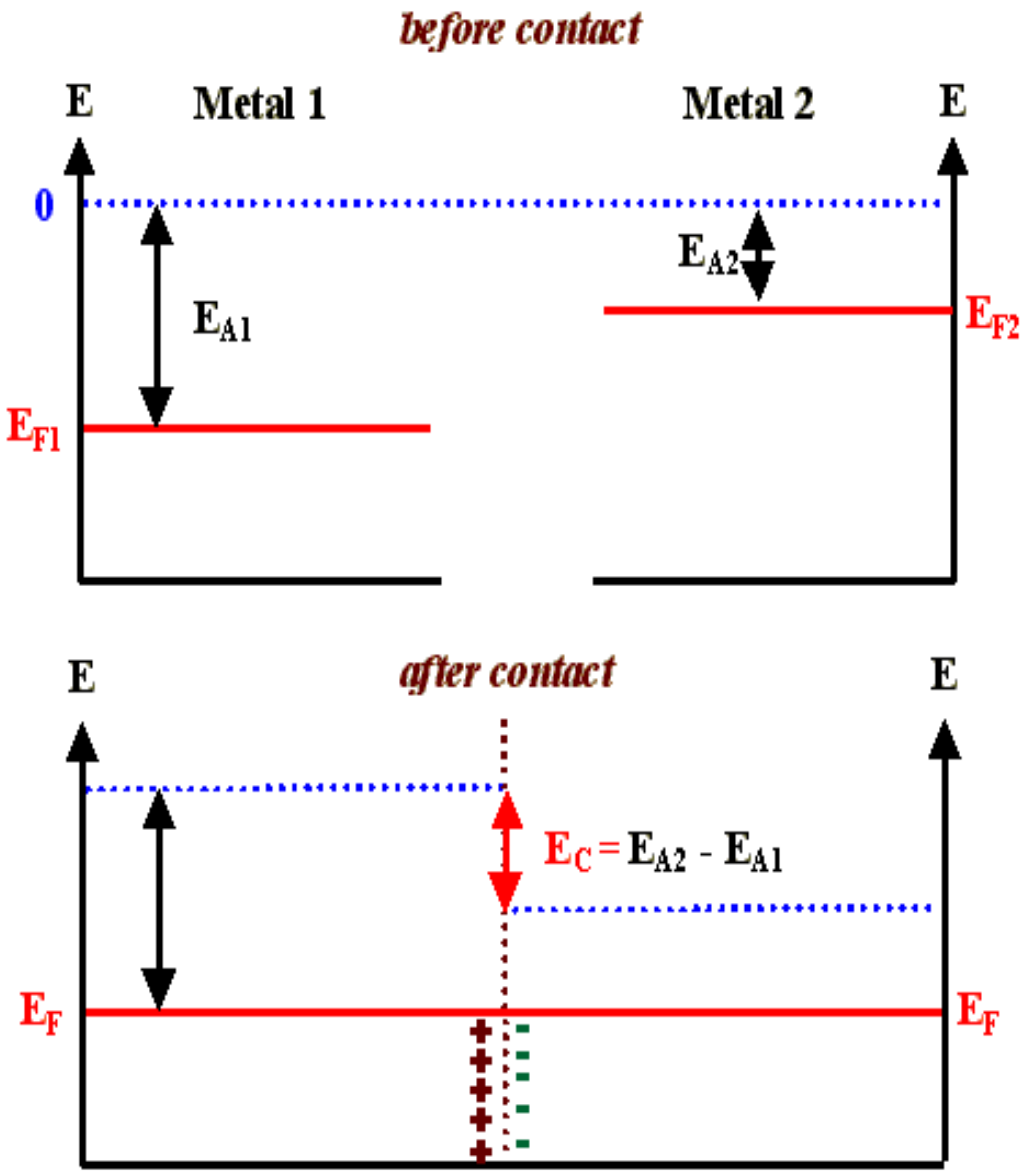
- $_T$Hydrogen chemisorbed diamond surface showed a minimum work function value of 4.8 eV.
- Oxygen chemisorbed diamond surface, which showed a maximum work function value of 5.8 eV.
- The surface potential value, which corresponds to the surface work function value, was strongly influenced by the species of the chemisorption on the diamond surface.
- The surface work functions were strongly correlated with the surface electronic states.
- A change of the chemisorbed species on the surface sensitively affected the surface work function.

H Gamo et al., Journal of Physics: Conference Series **61** (2007) 327–331

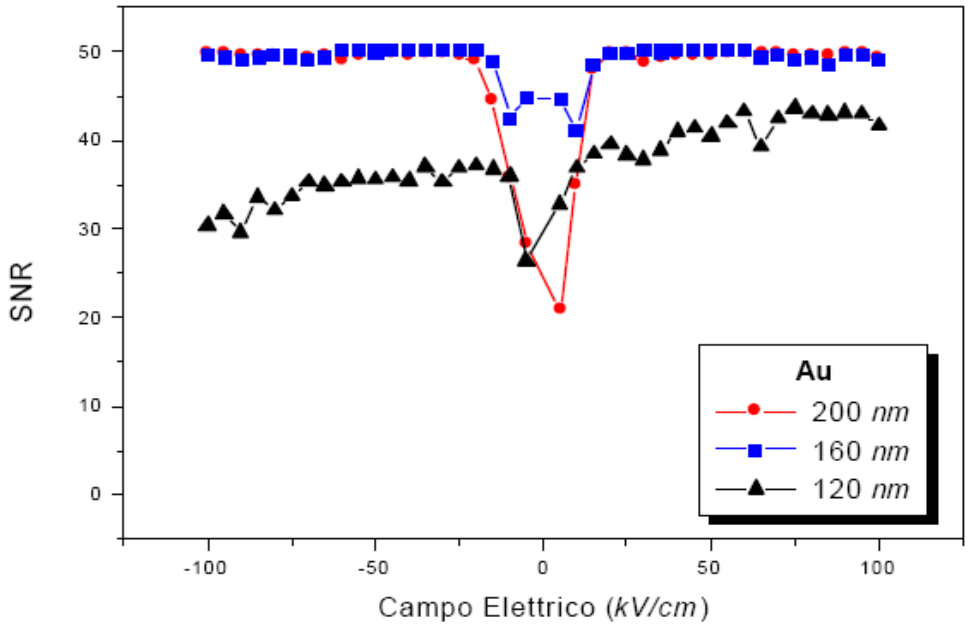
When two metals are electrically isolated from each other, an arbitrary potential difference may exist between them. However, when two different metals are brought into contact, electrons will flow from the metal with a lower work function to the metal with the higher work function

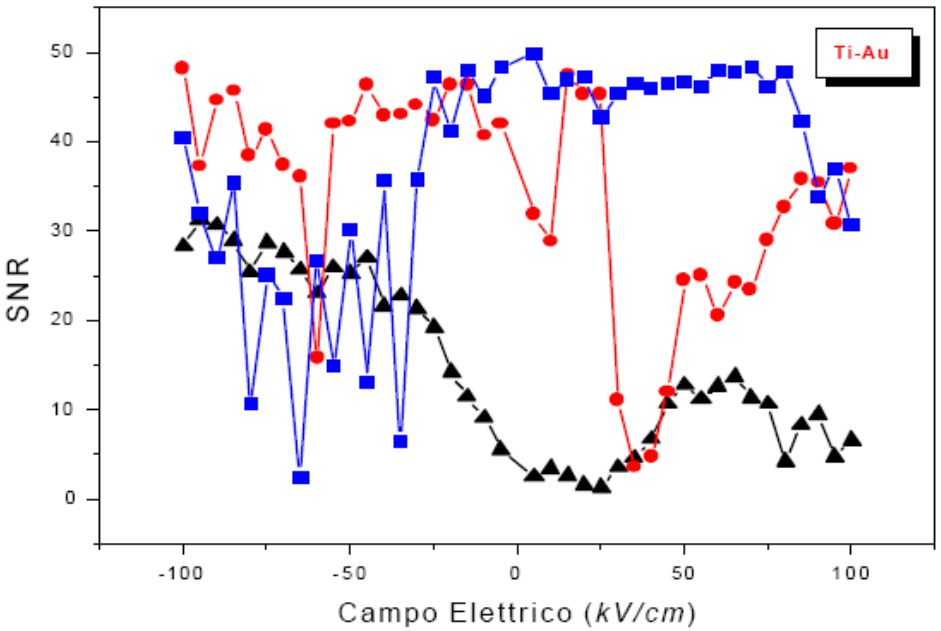
If two metals having differing work functions are touched together, one steals electrons from the other, and the opposite net charges grow larger and larger; this is the Volta effect. The process is halted when the voltage between the two metals reaches a particular value (the difference in work function values; usually less than one volt.)

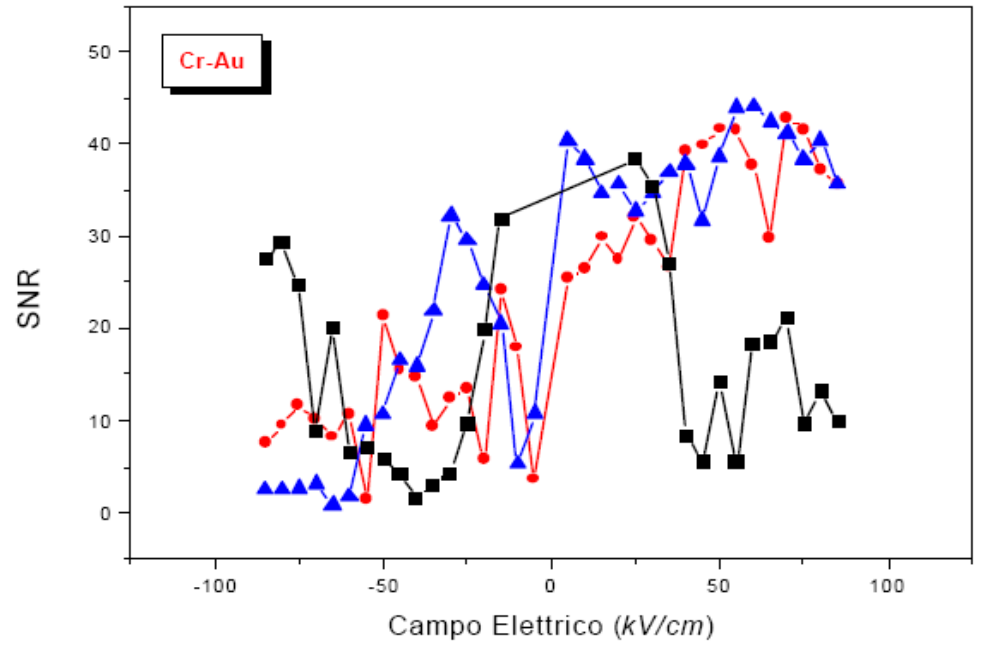
If metal touches a semiconductive material, or if two different semiconductors are placed into contact, one becomes charged slightly positive and the other slightly negative. It is found that if this junction between semiconductors is connected to a power supply, and if the power supply is set to a voltage slightly higher than the natural voltage appearing because of contact electrification, then for one polarity of voltage there will be a current between the two semiconductor parts, but if the polarity is reversed, the current stops.

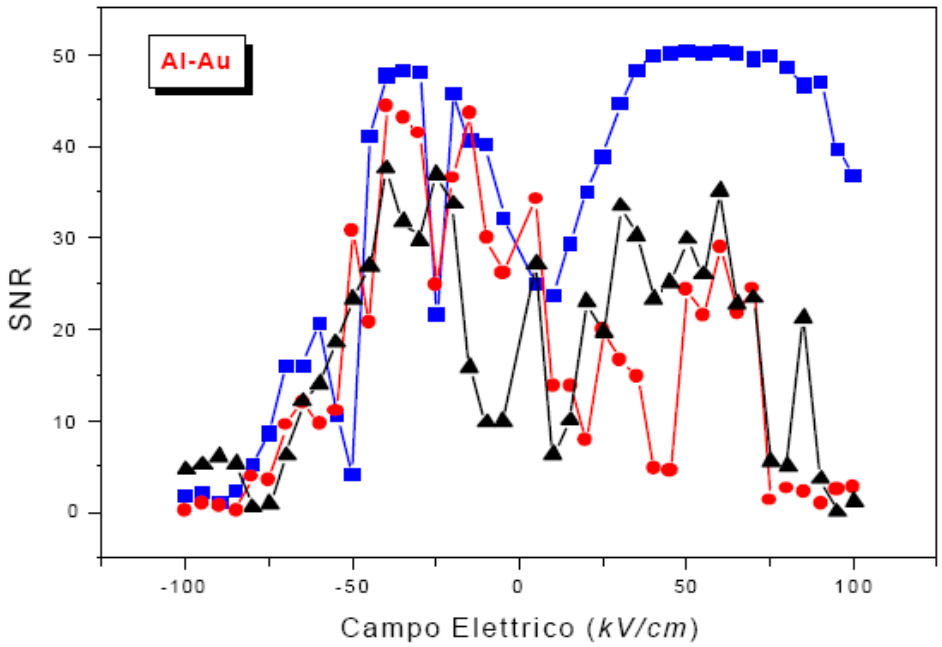


Influence of metal–diamond interfaces on the response of UV photoconductors









R. Di Benedetto et al. / Diamond and Related Materials 10 (2001) 698–705

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Chromium-Au Contacts
30 kVp X-ray Response

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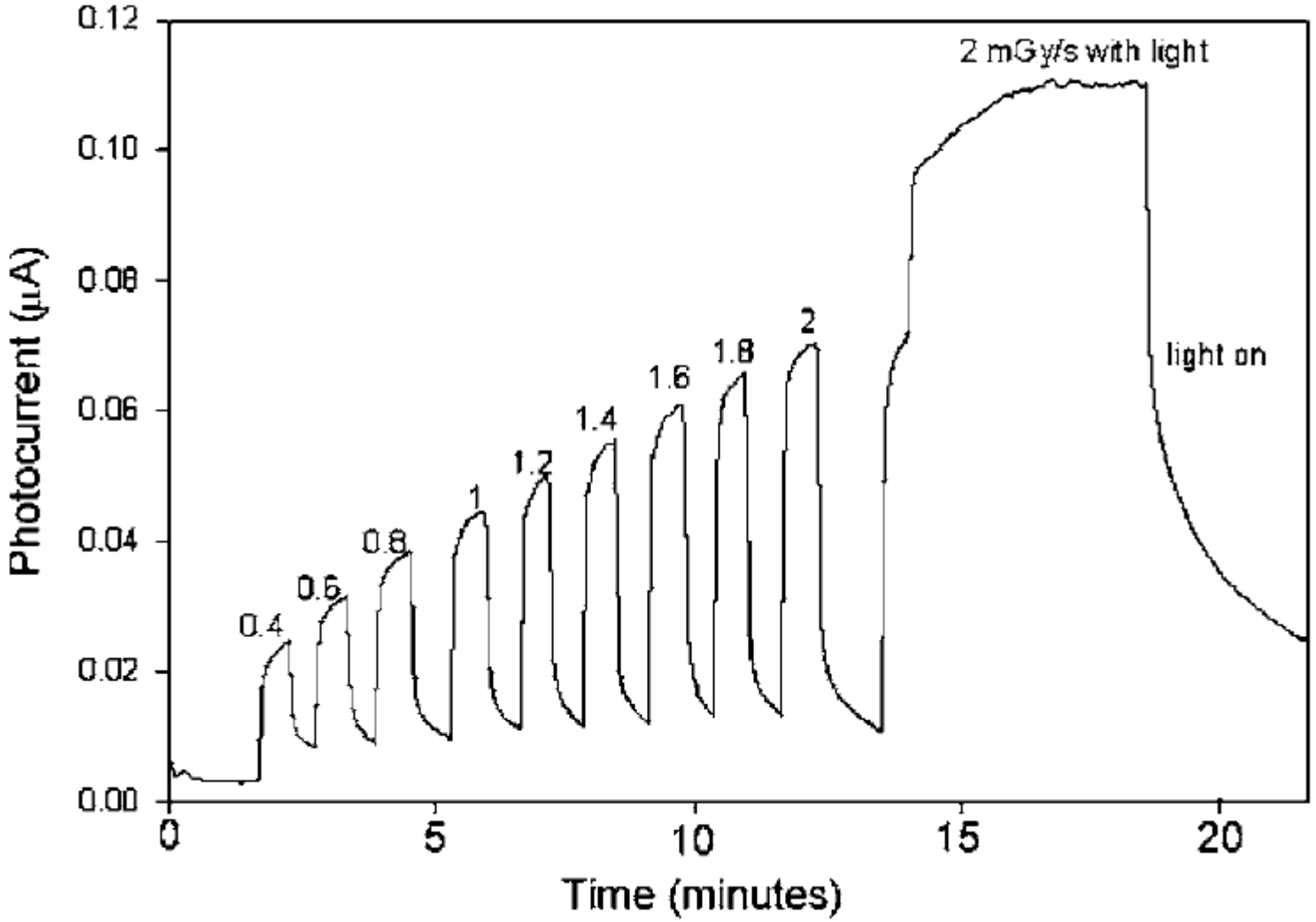

Graphitised-Boron Doped Contacts

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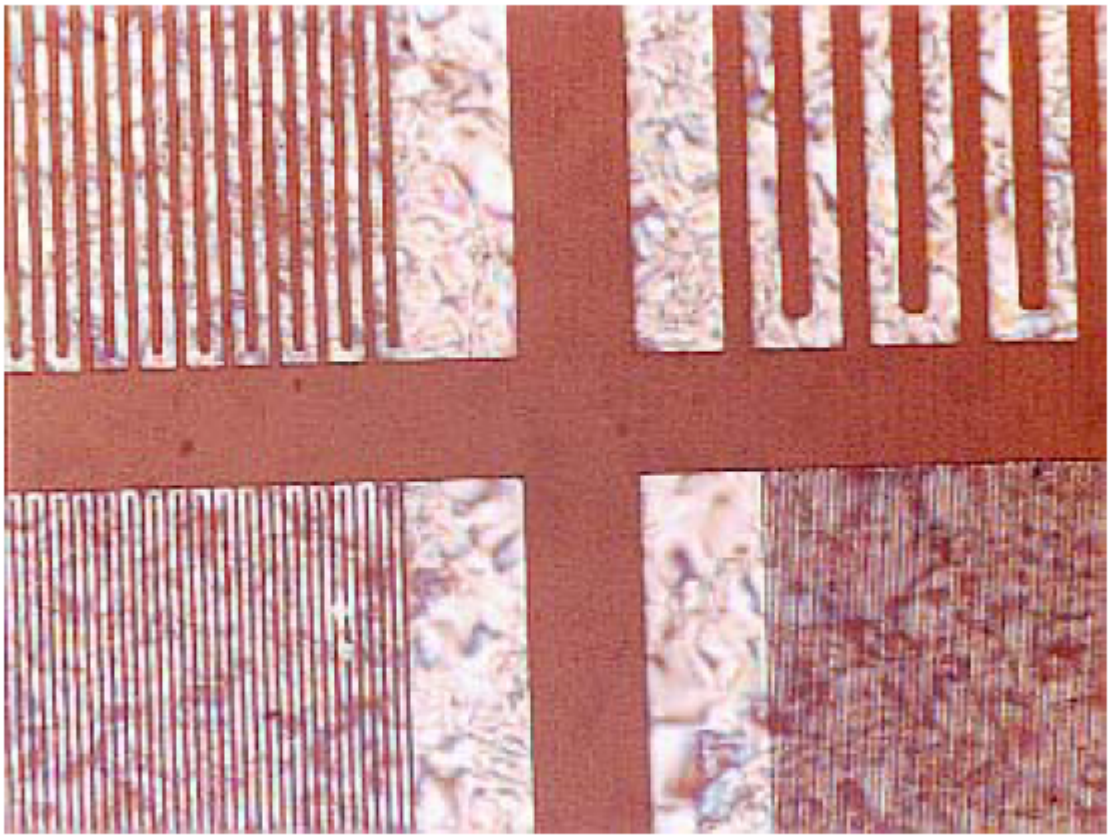
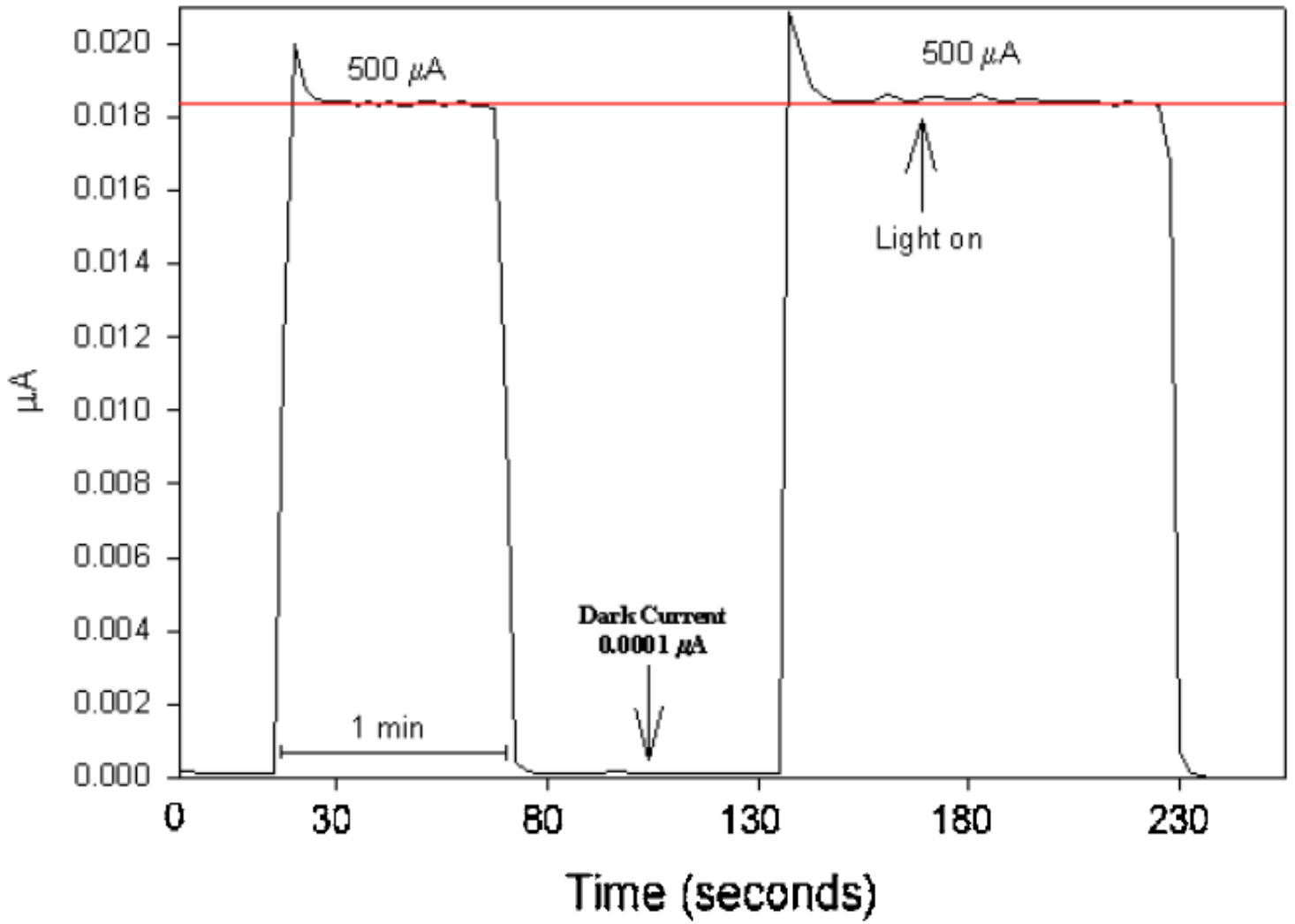


Figure 4-13: Phase Contrast Microscopy Image, BG devices

Graphitised-Boron Doped Contacts
30 kVp X-ray Response



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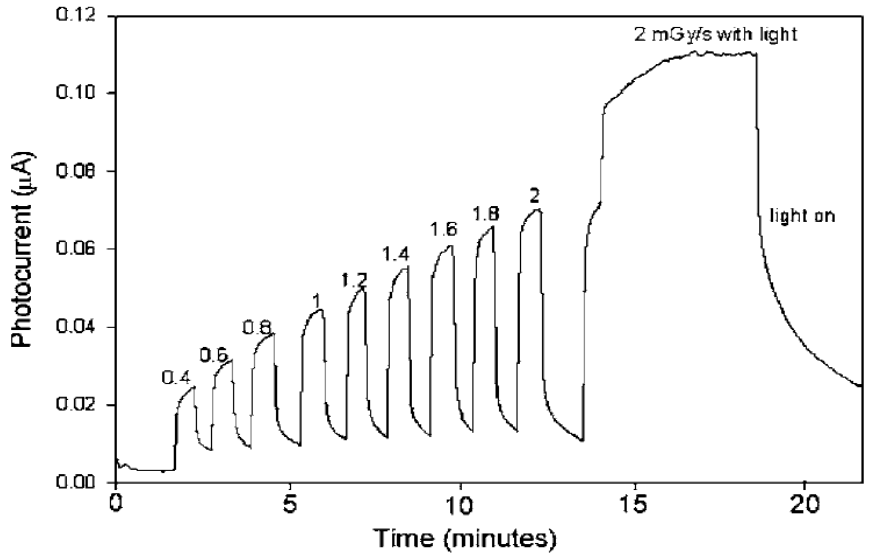
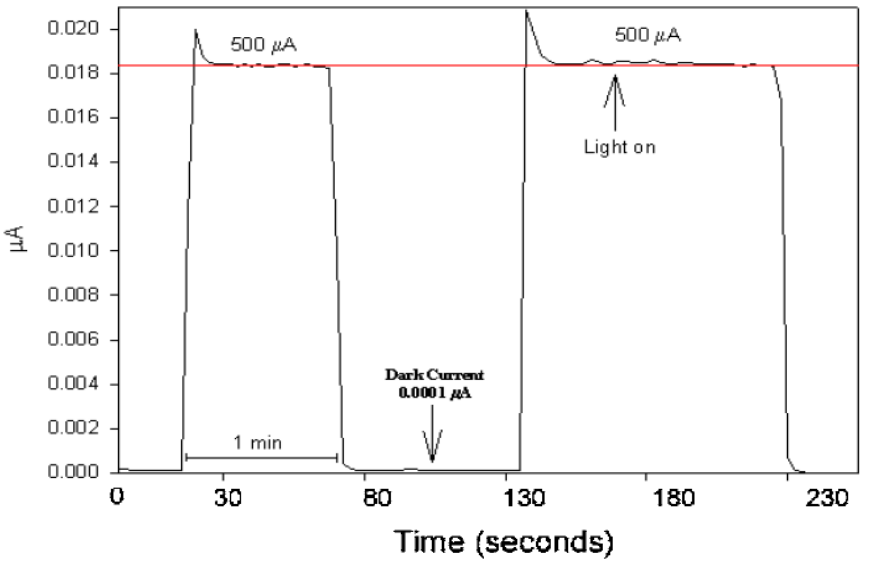
Graphitised-Boron Doped Contacts
30 kVp X-ray Response





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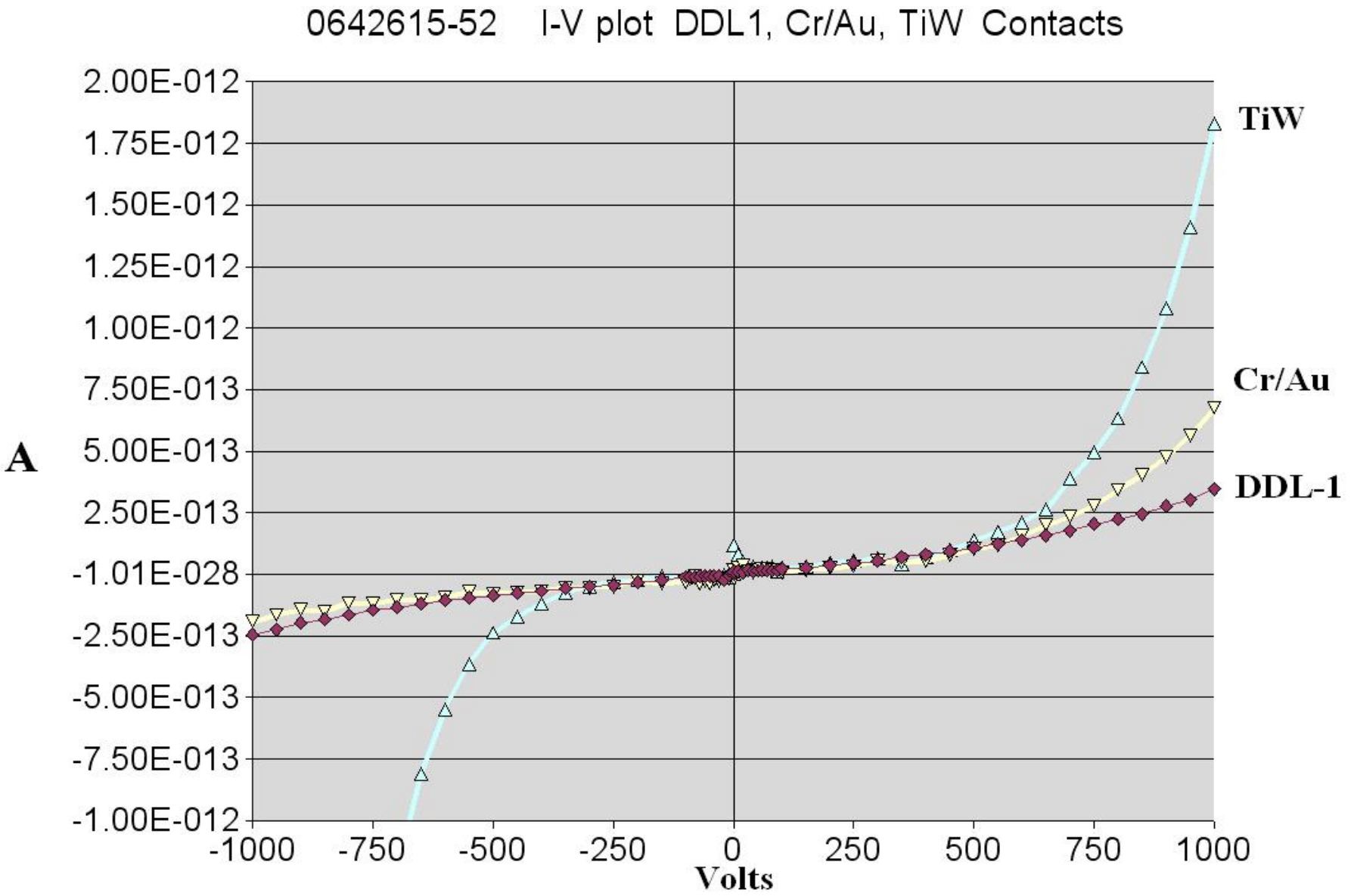
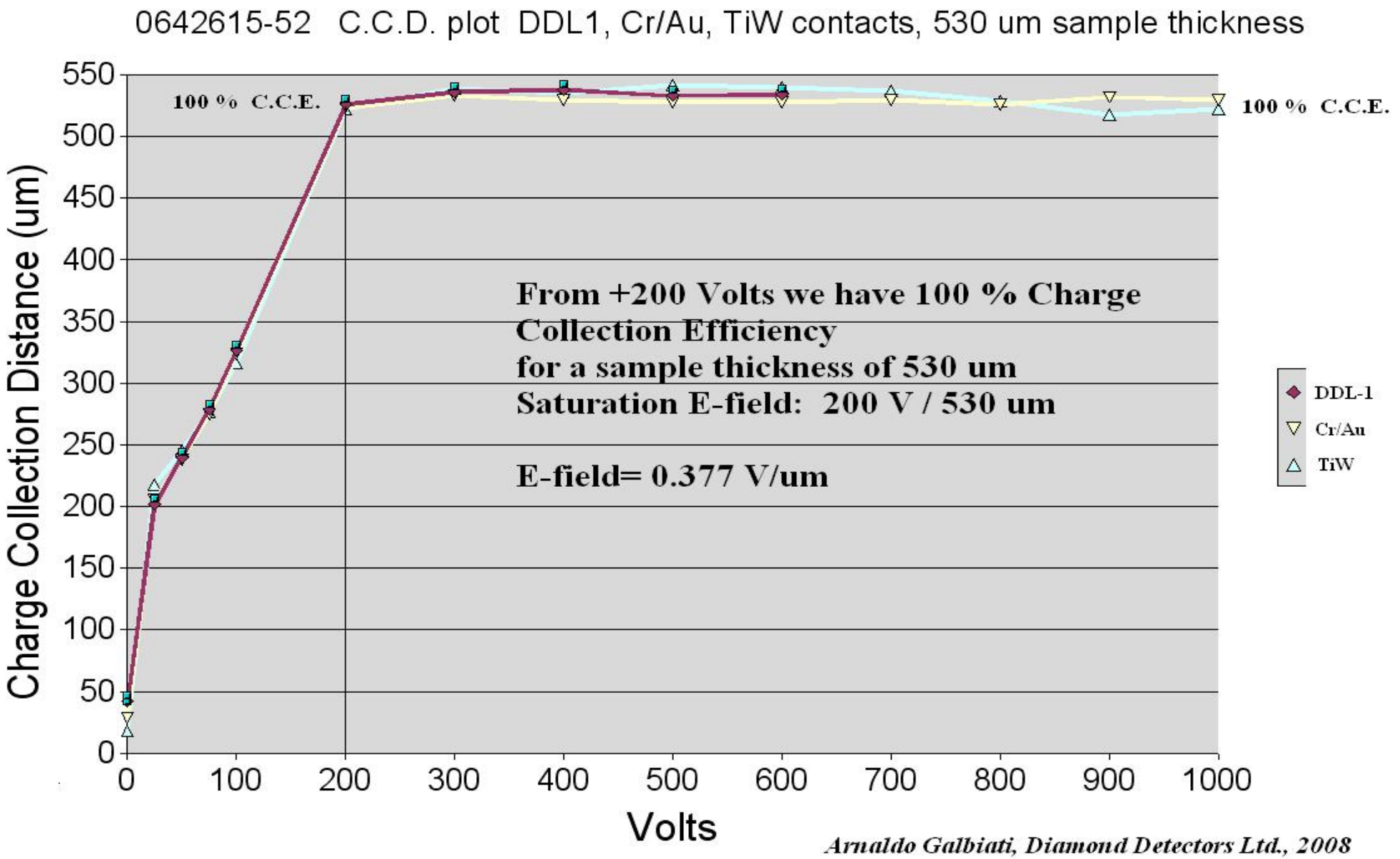
I-V Characteristic

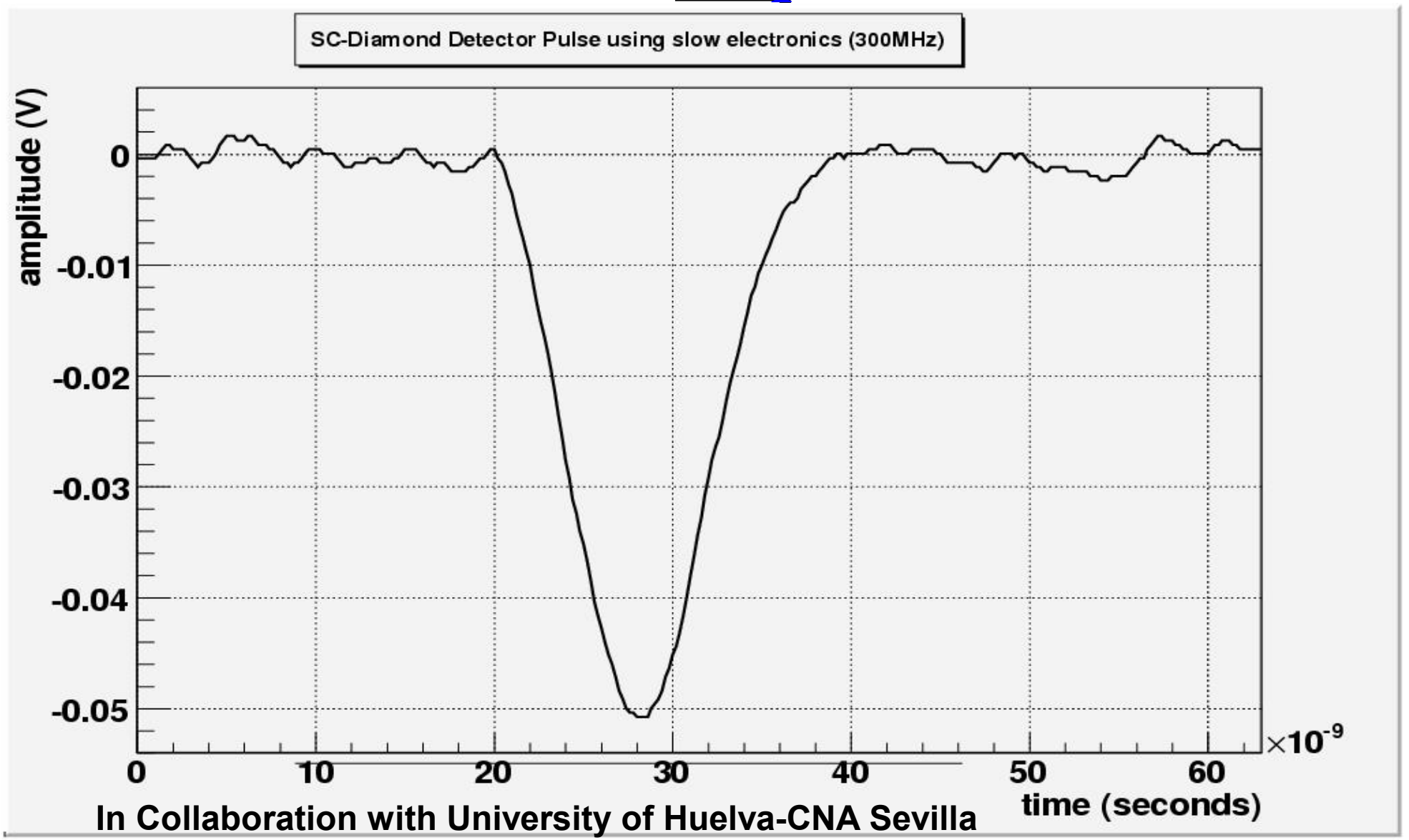


Arnaldo Galbiati, Diamond Detectors Ltd., 2008

Response under Sr-90 e^-



Single Pulse under Am-241 5.5 MeV α–particles



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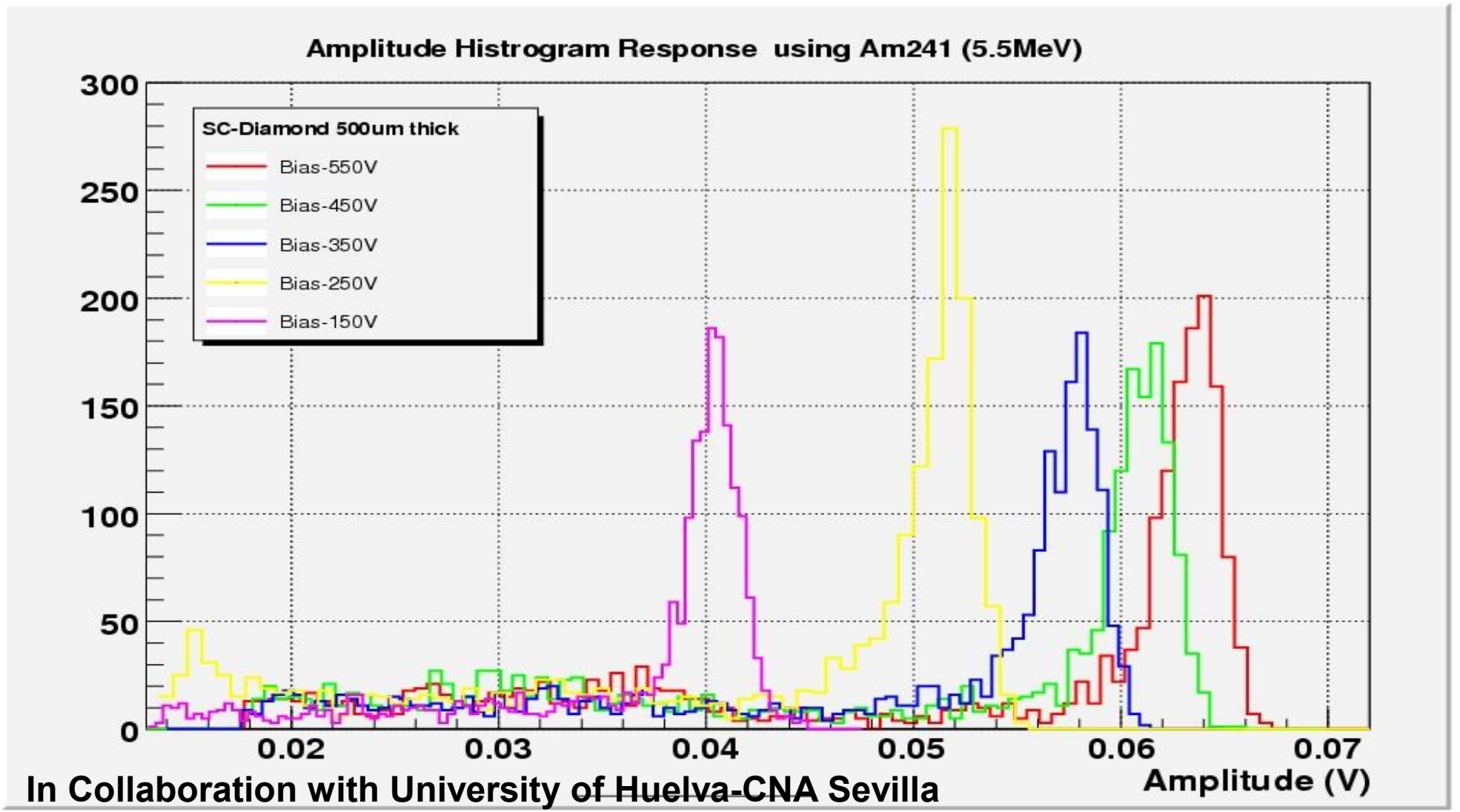
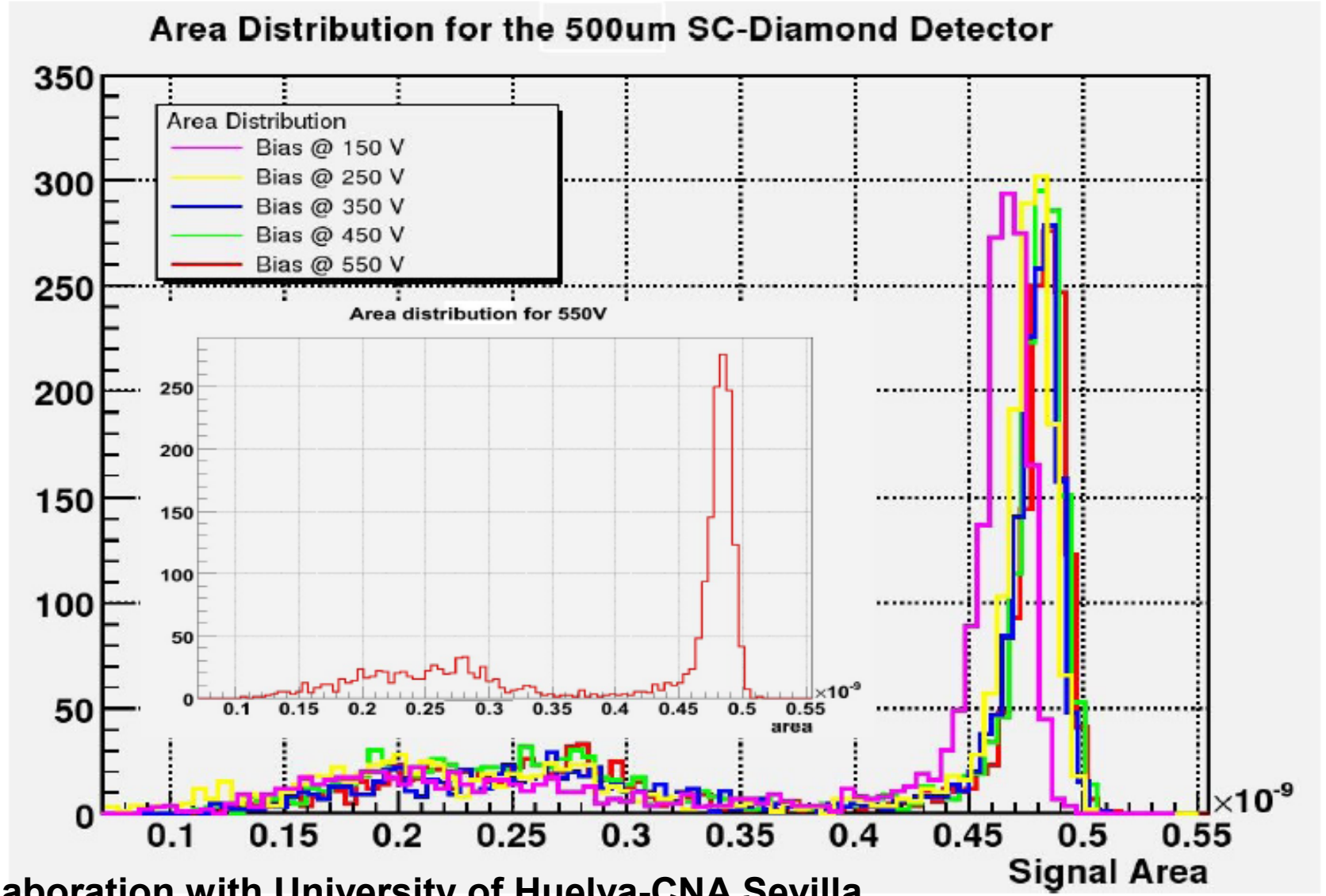
Response under Am-241 5.5 MeV α-particles



In Collaboration with University of Huelva-CNA Sevilla

DIAMOND DETECTORS LIMITED

Response under Am-241 5.5 MeV α-particles



In Collaboration with University of Huelva-CNA Sevilla

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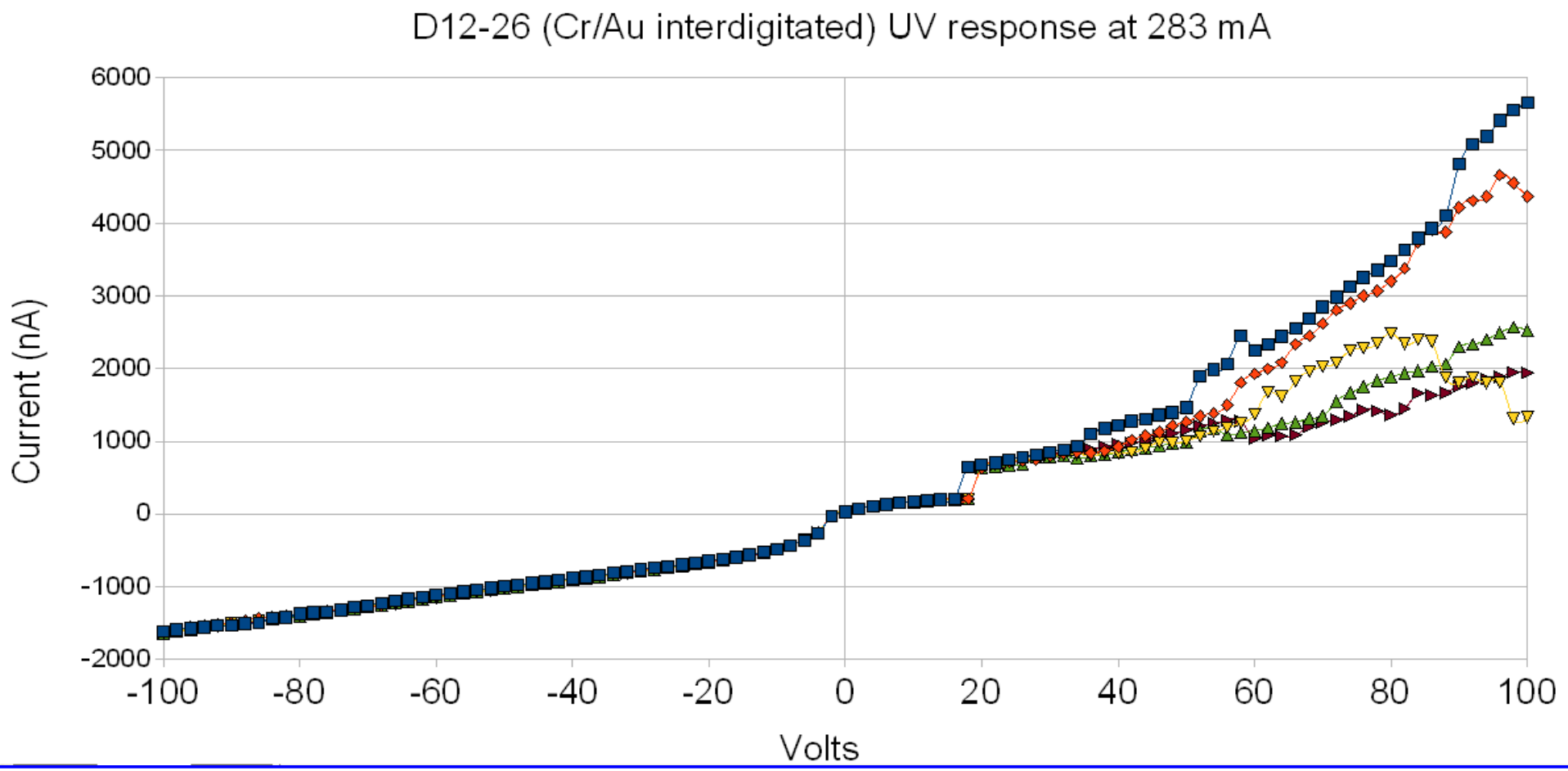
UV Response (Cr/Au contact)



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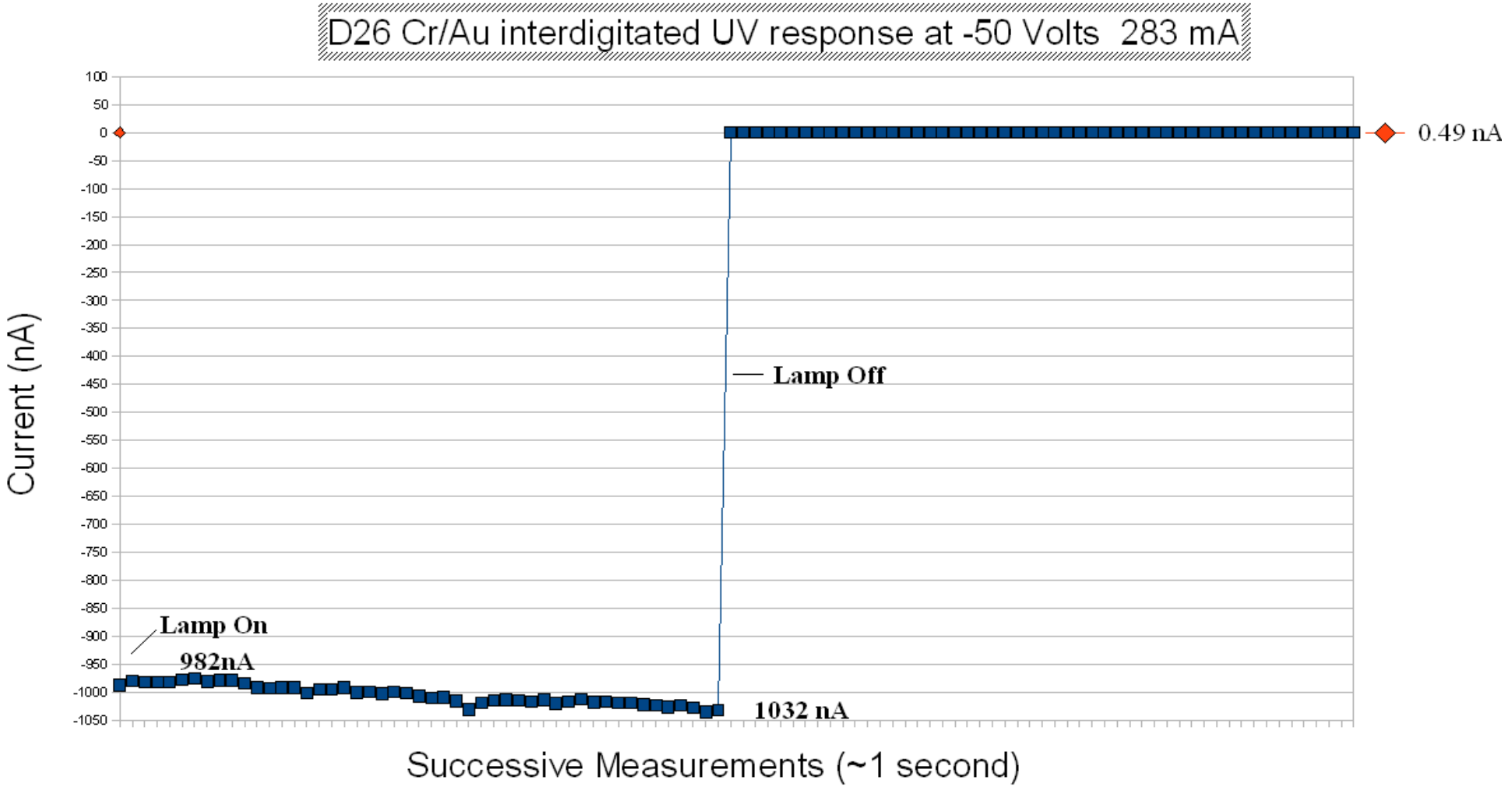
UV Response (Cr/Au contact)



Arnaldo.Galbiati@DiamondDetectors.com

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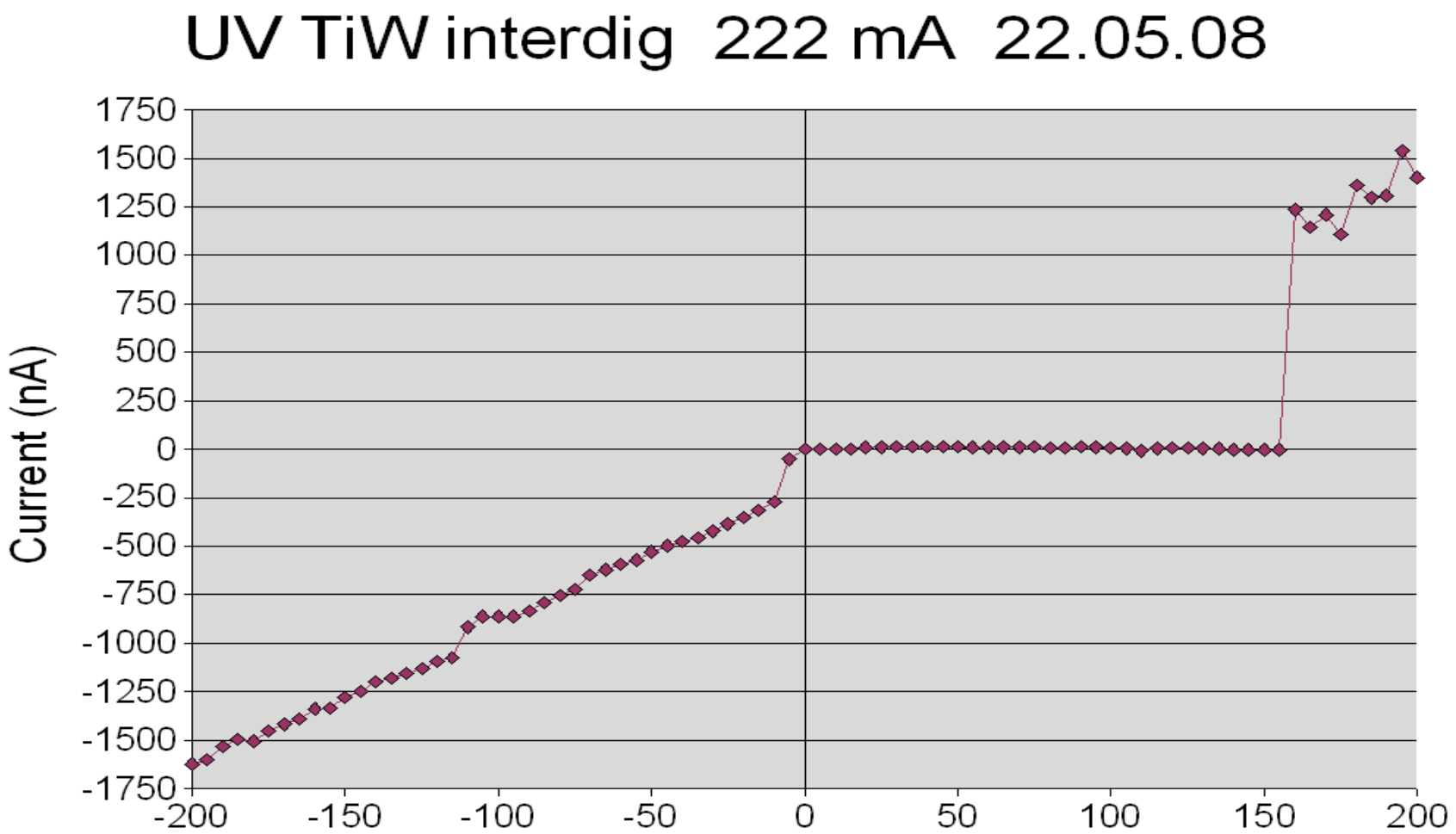
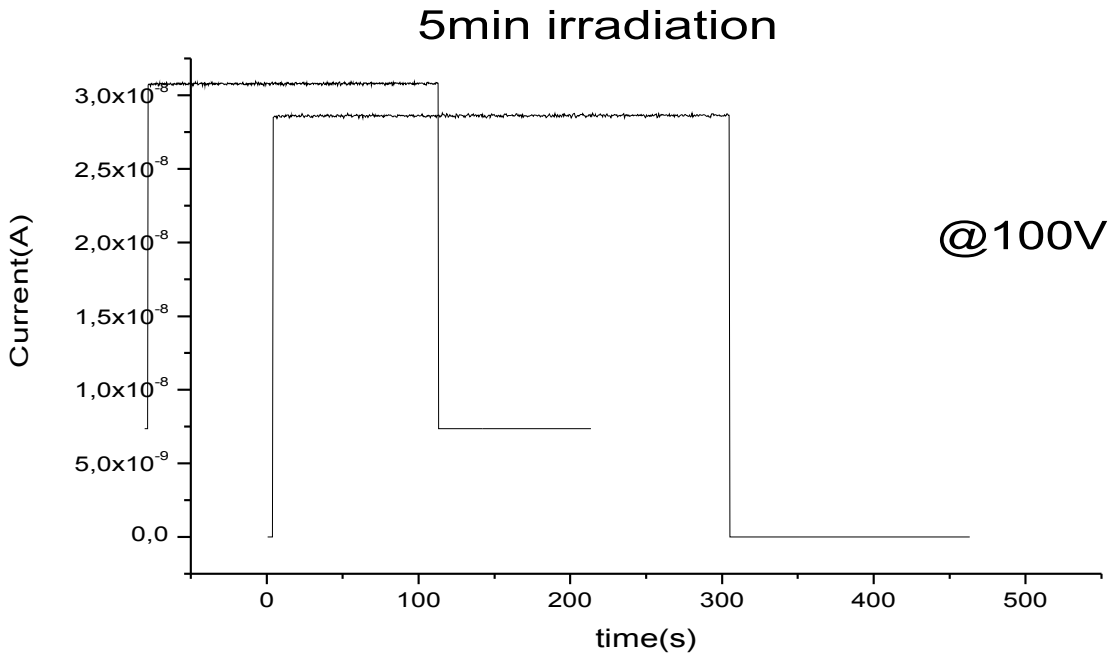
UV Response (TiW contact)



DDL Contact Radiotherapy Dosimetry Co 60 Response

Next positive biases were applied (500V, 250V, 100V, 50V, 10V). For these biases the sample showed very good behavior under irradiation. For example, considering a bias of 100V the sample shows very fast response while the source is switched on/off, absence of priming effect and very low fluctuation of the signal (that is below 0.5%). The signal to noise ratio is very high and about S/N ~ $3.3 \cdot 10^4$.



The response velocity of the sample was checked recording the data every 0.2 seconds. It is possible to see that when the source is switched on the sample reach the stabilization in a time that is less then 0.2 seconds.

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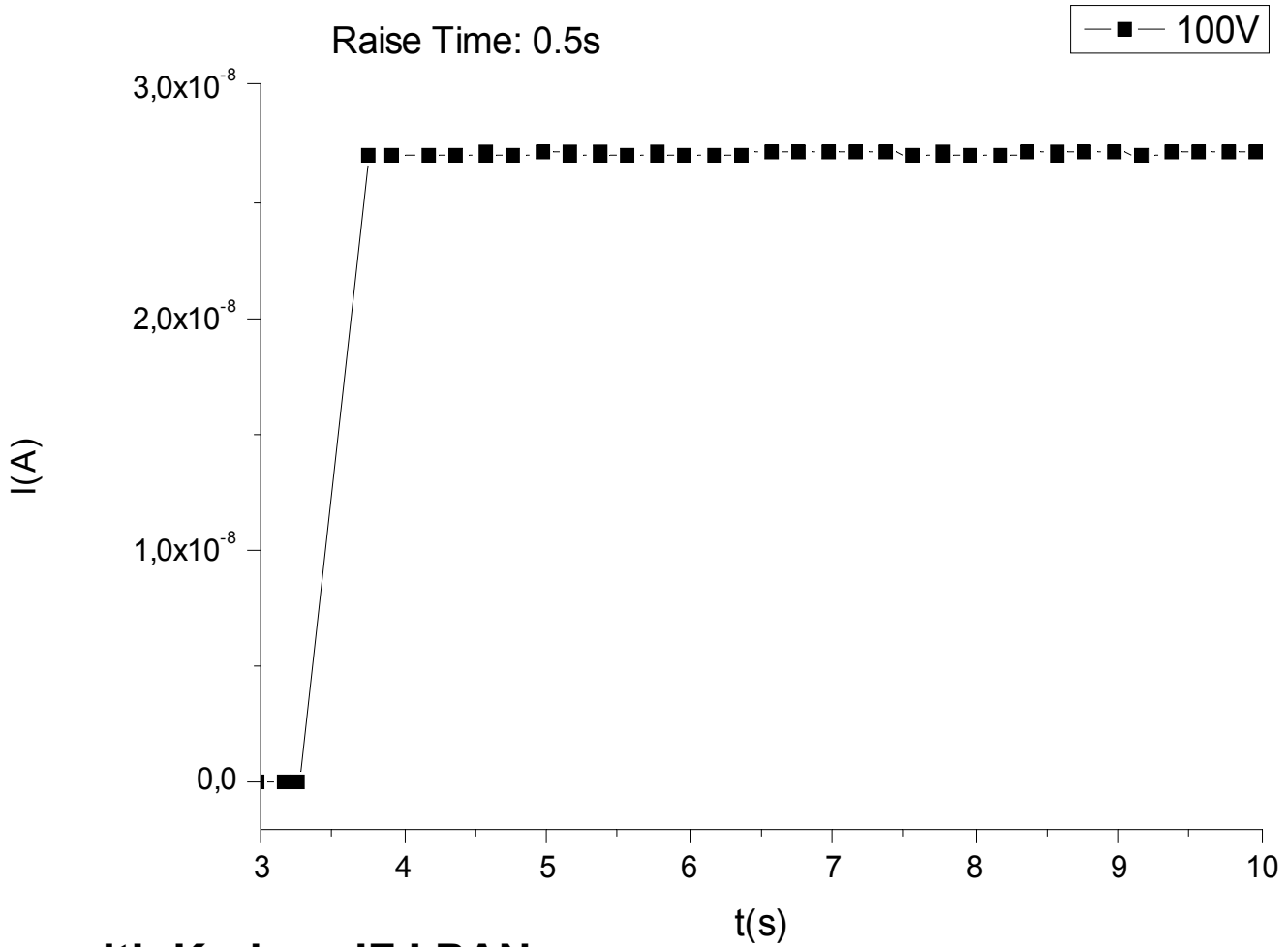
DDL Contact Radiotherapy Dosimetry Co 60 Response



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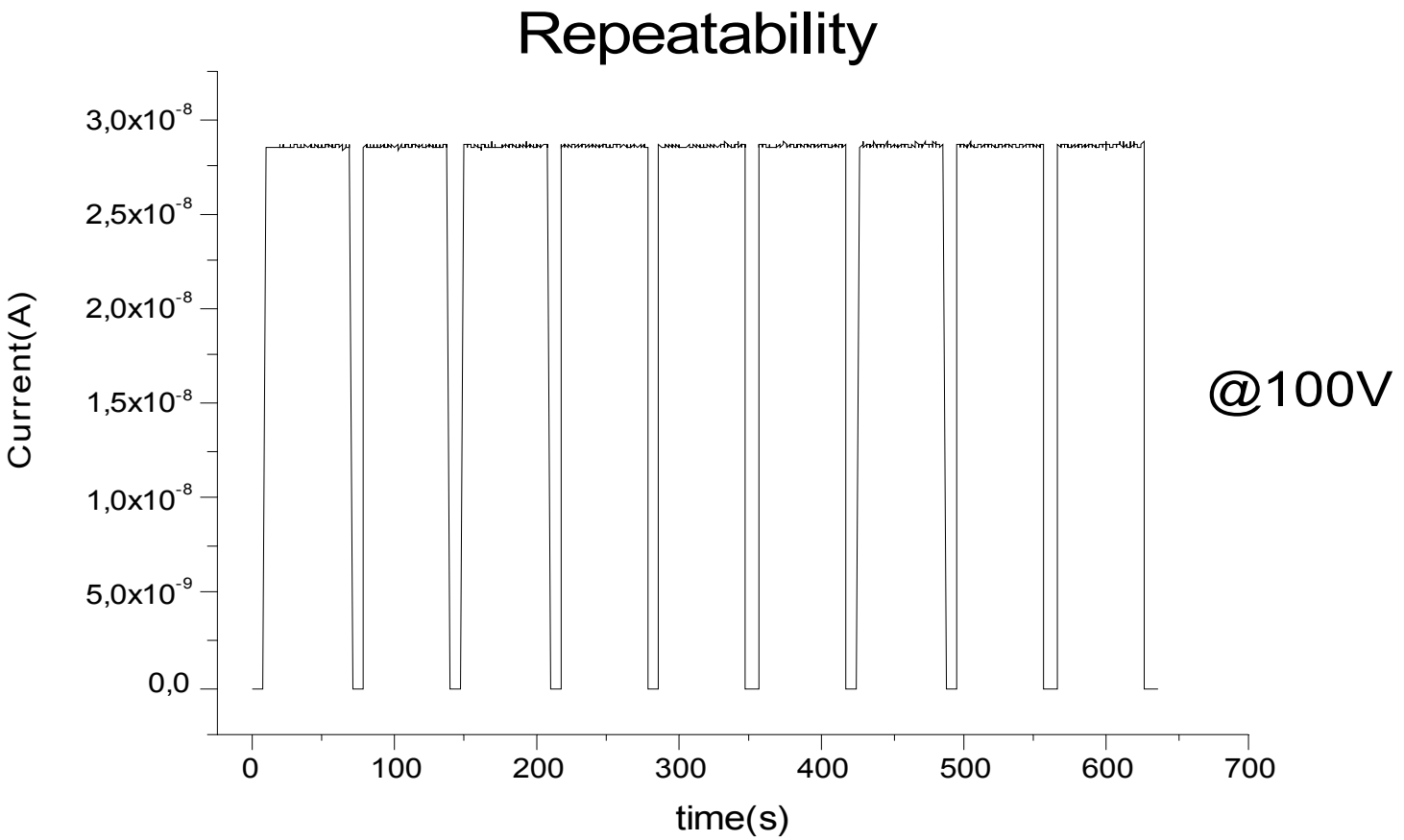
DDL Contact Radiotherapy Dosimetry Co 60 Response

To check the repeatability of the signal, one measurement was repeated several times at the same operating conditions. Each measurement in this case lasts one minute with a break of about 10 seconds. Taking the integral of each pulsed irradiation and averaging the values of area a coefficient of repeatability below 0.5% was found.



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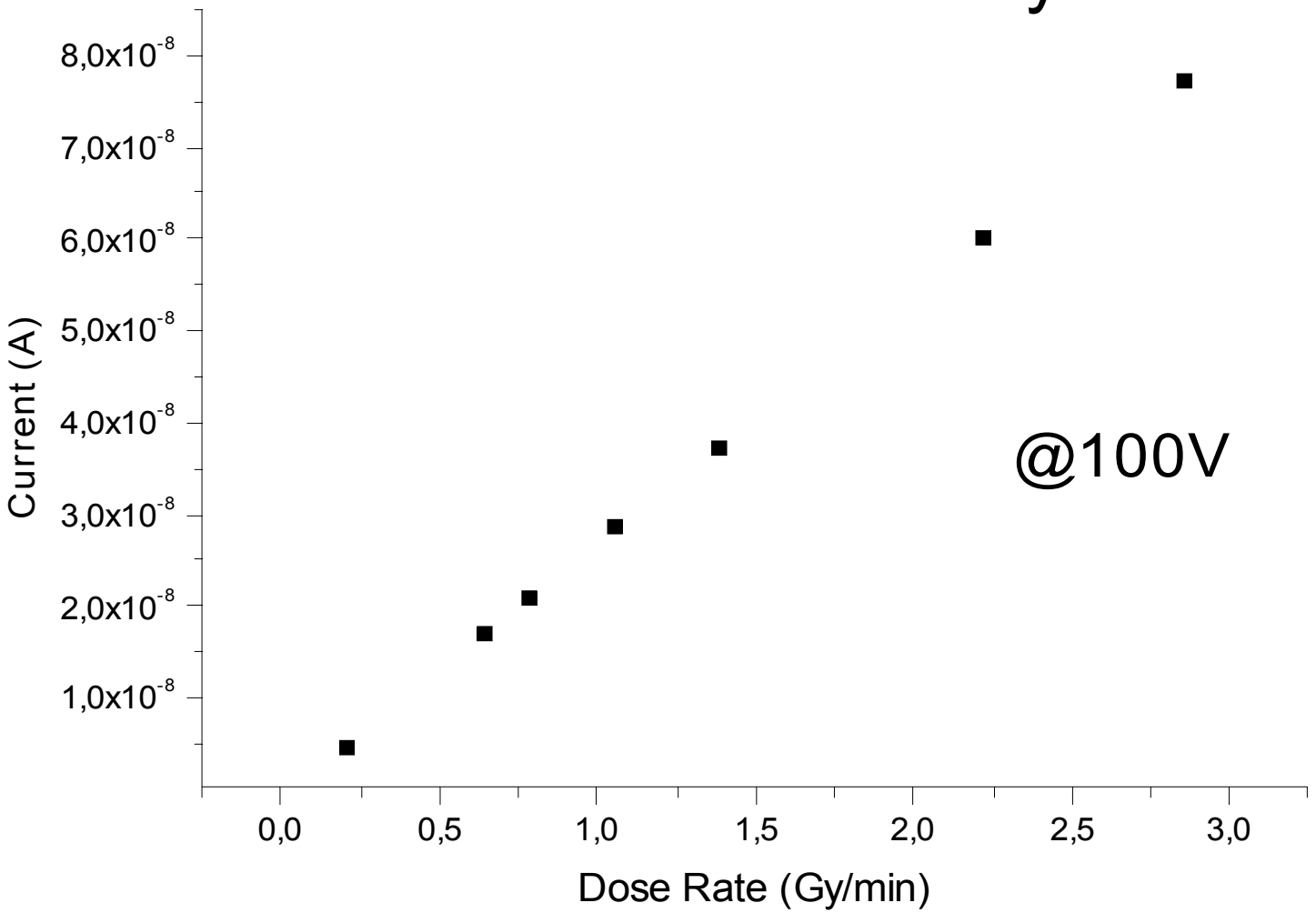
DDL Contact Radiotherapy Dosimetry Co 60 Response



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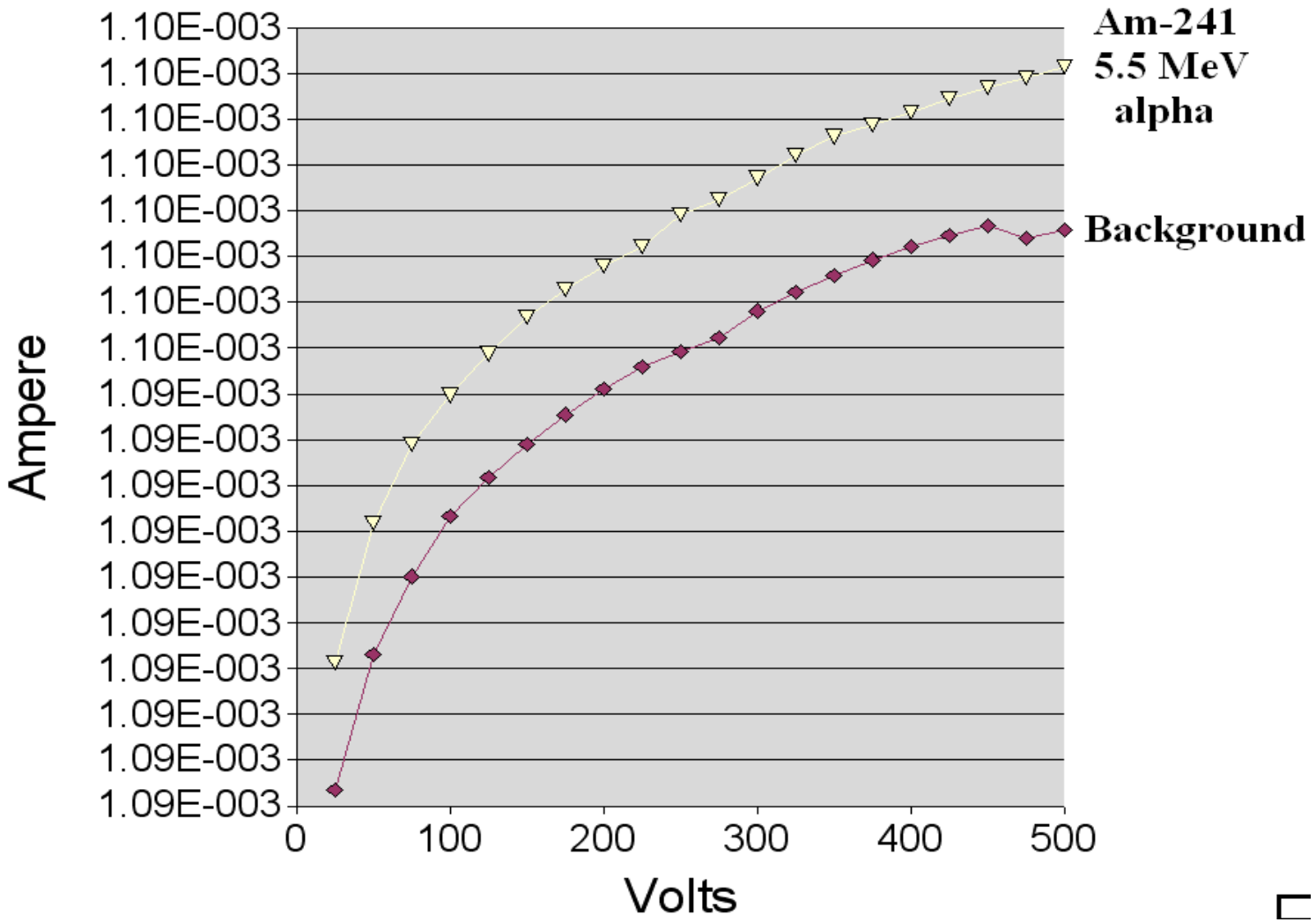
DDL
Diamond Phototransistor

25	1.085E-03	1.088E-03
50	1.088E-03	1.091E-03
75	1.090E-03	1.093E-03
100	1.091E-03	1.094E-03
125	1.092E-03	1.095E-03
150	1.093E-03	1.096E-03
175	1.094E-03	1.096E-03
200	1.094E-03	1.097E-03
225	1.095E-03	1.097E-03
250	1.095E-03	1.098E-03
275	1.095E-03	1.098E-03
300	1.096E-03	1.099E-03
325	1.096E-03	1.099E-03
350	1.097E-03	1.100E-03
375	1.097E-03	1.100E-03
400	1.097E-03	1.100E-03
425	1.097E-03	1.100E-03
450	1.098E-03	1.101E-03
475	1.097E-03	1.101E-03
500	1.098E-03	1.101E-03



Arnaldo Galbiati

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Conclusions:

We have a different device according to the metallization used!