3 Radiation detection.

3.1 Detector modeling.

To master all the device characteristics apt to allow a successful tailoring of a detector with performance as close as an ideal dosimeter, it seemed necessary to start with a critical analysis of the accepted interpretative model descriptions of the radiation induced response of a solid state detector.

The development of a reasonable model, necessarily supported by experimental results, is mandatory for the comprehension of the working mechanisms of the devices and, consequently, it is fundamental for the device optimisation and reproducibility. We suppose that diamond based-detectors act as solid-state ionisation chamber, the benchmark of the dosimeters for dosimetry applications. The generally accepted Fowler's model for solid-state dosimetry is applicable only for detectors working in specific conditions, consequently a new model was developed and it is described in the following.

3.1.1 Solid state dosimetry model.

The theoretical background involving the solid state dosimeter response was established by Fowler[1] and it is based on the time dynamic expression derived from the continuity equation for a hypothetic n-type semiconductor (a symmetrical analysis can be done for a p-type semiconductor) characterized by a continuum defect state energy band gap:

$$\frac{dn_{Ph}}{dt} = G_0 - \frac{n_{Ph}}{\tau} - \frac{n_{Ph}^{\ 2}}{A} \cong G_0 - \frac{n_{Ph}}{\tau}, \tag{1}$$

where n_{Ph} is the excess photo generated carrier density, G_0 the electron-holes generation rate within the crystal, τ the trapping mean lifetime, A the band-to-band recombination coefficient between electrons and holes. If we consider stationary conditions, that is $dn_{Ph}(t)/dt = 0$, we find that for an ideal crystal $A<<\tau$. In this case, the electron-hole recombination represents the prevalent effect and this produces a square root-type dependence of excess carrier density as a function of generation rate ($n_{Ph} = (AG_0)^{1/2}$). Otherwise, for a semiconductor with a large density of traps, the quadratic term can be neglected, causing a linear dependence on G_0 (but a reduced sensitivity):

$$n_{Ph} = G_0 \tau \,. \tag{2}$$

In this case, the photocurrent density under stationary conduction conditions is given by:

$$J_{Ph} = \sigma F = qG_0 \mu \tau F \,, \tag{3}$$

where τ is the semiconductor excess conductivity, which is generated under irradiation conditions in respect to the dark one and defined as the product of the elementary electron charge, the semiconductor mobility and the excess carrier density, defined in equation Eq. (1). This theory does not necessary grant the linearity with the radiation intensity because the terms μ or τ may depend on the generation rate (for example in high charge carrier injection conditions), so the photocurrent may follow the more general law:

$$J_{Ph} \propto D^{\gamma} \,, \tag{4}$$

where $0.5<\gamma<1$. Furthermore, Fowler's theory is defined only in the ohmic range of photoconduction. We have to introduce a new model in order to interpret the more complex behavior of our detector.

3.1.2 Solid-State ionization chamber. Photo-detection model.

The model we propose is based on the charge induction process: a semiconductor, subjected to an excitation process which creates excess charge carriers and subjected to the application of an external electric field, produces immediately a current pulse due the charges induced on the electrodes.

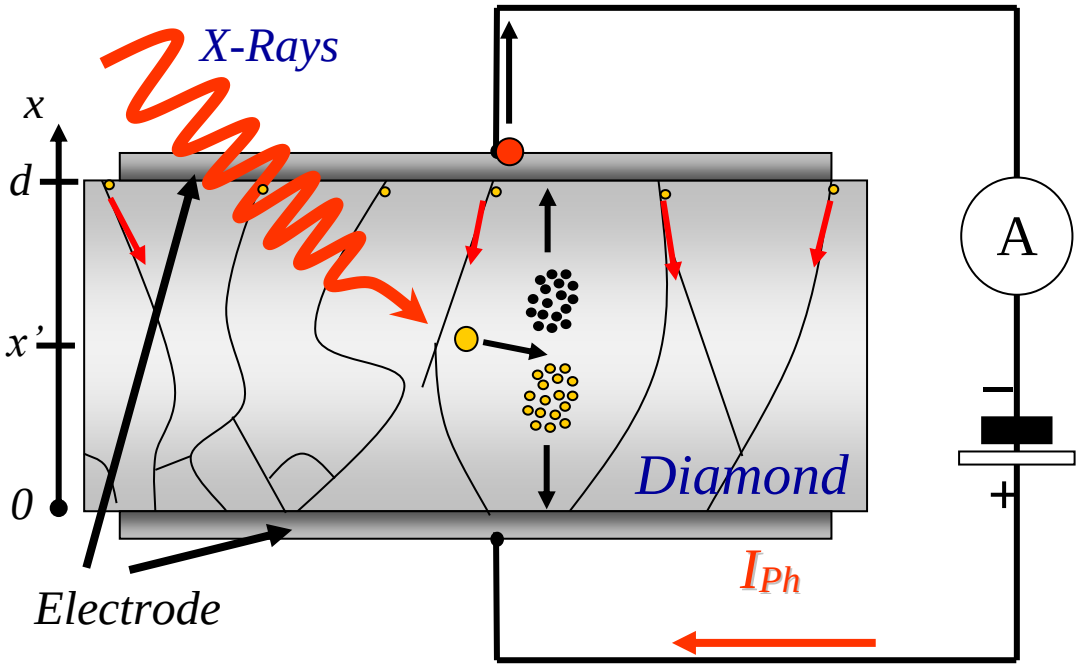

Fig. 10

Furthermore, a device, made of a high electric resistivity semiconductor, structured in a *sandwich* configuration with thickness *d*, acts like a parallel plate capacitor (Fig. 10). If the excitation is a ionising radiation producing $Q_{ionised}$ excess carriers uniformly in the semiconductor (like our x-ray beam), we define $Q_{collected} = Q^{n}_{collected} + Q^{p}_{collected}$ as the excess charges effectively collected to the electrodes. It can be defined a collection efficiency for such a device[2]:

$$\eta_C^{n,p} = \frac{Q^{n,p}_{collected}}{Q_{ionised}} = \frac{L_C}{d}\left[1 - \frac{L_C}{d}\left(1 - \exp\left(-\frac{d}{L_C}\right)\right)\right] \qquad (5)$$

where $L_C(V) = \mu\tau V / d$ is defined as the collection length for electrons and holes, being μ and τ respectively mobility and lifetime of the charge carriers and V the bias voltage. The collection efficiency defined in (5) is similar to the Hecht's equation[3], frequently used for describing photo-conduction phenomena in semiconductors, but that formula is specific for the case of carrier generation only near one electrode and not uniformly along all the detector. The induced total photocurrent density is expressed as

$$J_{Ph}(V) = qG_0 d\,\eta_c(V) \qquad (6)$$

where G_0 is the generation rate, namely the volume concentration of generated carriers per unit time. The photocurrent expression (6), largely influenced by the L_C / d ratio, can be simplified for the two limiting cases, as:

$$J_{Ph}(V) = qG_0\,\mu\tau V, \quad L_c < d, \qquad (7)$$

$$J_{Ph}(V) = qG_0 d/2, \quad L_c >> d. \qquad (8)$$

The ideal dosimeter has to assure the linearity between the physical observable, the signal generated by the radiation and the quantity to be measured, namely the exposure absorbed dose-rate, which is the absorbed energy per unit time and unit mass and is proportional to G_0. Due to the process of carrier generation, we suppose that the absorption of the radiation dose can be totally ascribed to the photoelectric effect, with a mechanism consisting in a sudden elastic transfer of energy from photon to the material and successive cascade transfers up to the generation of low energy carriers (Fig. 10). In such a way, the condition of linear response is reduced to the proportionality between the recorded signal and G_0.

Apparently, Eq. (7) could only show a limited range of a linear behaviour of the response, because it is well-known that, for a distribution of trap levels in the energy gap and for high generation conditions, carrier mobility or lifetime may be function[4] of G_0: as a consequence the photocurrent cannot be considered in the whole range proportional to the radiation absorbed dose-rate. On the other hand, the conditions evidenced by Eq. (8) seem to be the only one able to guarantee a linear relationship, defining the collection length much greater than *d* as the optimal working condition for a detector capable of linear response. Practically, once fixed the material properties modifying the deposition parameters, the only variable parameter able to induce an increase of the collection length in order to ensure the linearity is the increasing of bias voltage. Moreover for transversal working devices, the design of thin thickness implies two advantages: the application, at a fixed voltage, of a higher electric field and the minimization of the contact distance, both factors that concordantly contribute to reach the condition $L_C >> d$.

At this point of the discussion, the importance of the contacts becomes determining in order to understand the detector response, since the nature of the contacts represents the boundary conditions of the model for collection distances comparable or greater than *d*. If the device presents ohmic contacts, no surface barrier exists at the diamond-metal interface and the device thickness is always greater than the collection length because a continuous injection of carriers from one electrode to the other is possible. Such a situation is describable by Eq. (7) and, as discussed, does not completely grant the linearity.

On the other hand, if the contacts are blocking for one type of carriers, namely characterized by a blocking layer at the surface interface, a carrier that reaches the electrode is trapped by surface states and cannot be re-injected from the other electrode into the device. In such a way, varying the applied voltage, both the situations described by Eq.s (7) and (8) can be investigated.

It is very interesting to note that the detector emulates the working mechanisms of a parallel plate ionisation chamber, since the applied voltage influences the collection efficiency of the excess charges and consequently the response signal. In fact, both for the described detector and for the ionisation chamber, at low voltage, the excess charges can recombine and cannot reach the electrodes, while at sufficiently high voltages, the excess carriers gain a considerable drift velocity, succeeding in reaching the electrode. The ionisation chamber works in that region, a region that ensures a unitary collection efficiency, when the signal saturates and it does not depend anymore on the applied voltage, condition necessary and sufficient for a linear response.

As a consequence, the optimal prescription for linear solid state dosimeters seems to be determined by a blocking contact and bias voltage values able to allow carrier collection length greater than the electrodes distance. However the material should be not too resistive so that a static charge would counteract the action of the bias field.

3.2 Low energy x-ray detection setup

In order to completely analyze the devices and to simulate the behaviour of a real dosimeter, during this project a low energy x-ray characterization setup was built. It provides an initial selection test before the final analysis performed with the high energy radiotherapy facilities. The basic idea was that the samples had to follow a characterization protocol starting from the CNR-IMAO institute with their growth and initial morphological analysis. Samples were then prepared to become real devices (treatments, metallic contacts), and electrically and optically characterized by the INFM Roma Tre group. Finally, the devices showing a suitable electrical transport quality were tested for detection under an x-ray beam at the CNR-IMAO using the setup reported in Fig. 11. After this stage, the samples presenting suitable properties were sent to the radiotherapy facilities (UCSC, KI, Eurorad, SCX) for high energy radiation tests.

The x-ray photo-detection setup was designed to allow measurements under continuous and modulated radiation exposition. In this way it is possible to derive the current flowing into the device, the total current under irradiation and the net photo-generated current, at the variation of modulation frequency and bias voltage.

The X radiation is generated by a classic copper-target tube (Philips microfocus 10x1 mm2 filament), with a maximum acceleration voltage of about 45 kV (40 kV is the standard working value). The radiation is then absorbed by a Nickel filter (15~25 μm thick) in order to eliminate the CuKα line, so that the x-ray energy spectrum is composed only of Cu Kα line (8.06 keV) and of a very small part of white continuous spectrum (Bremmstrahlung), thus obtaining a quasi monochromatic radiation; this radiation is then forced to pass through a stainless steel collimator and a variable thickness filter for a controlled attenuation of the X-ray beam intensity: this technique is called the absorber method. The filter used is composed of a metallic material, usually aluminium, nickel or copper, which show a well-known and tabulated absorption curve and a low absorption coefficient. This allows us to have a large range of thickness variation. The beam, behind the controlled attenuation section, can be modulated in the 4 ~ 2500 Hz range by a mechanical chopper, 2 mm thick and composed of stainless steel, which guarantees a dark-light ratio of about 200 dB for the range of radiation energy examined (8 ~ 40 keV).

The beam impinges orthogonally on the device. The detector is biased by a voltage generator (Keithley model 487) in the range ± 500 V: in case of continuous excitation, the dark and photo-generated current are measured by a pico-ammeter (Keithley model 487), while in modulated excitation, the net current signal is amplified and converted in a voltage signal by a current-voltage converter (Signal Recovery model 5182) and sent to a lock-in amplifier (Signal Recovery model 5210), which compares the signal of interest with the reference one generated by the chopper controller.

With the introduction in the AC electronic chain of a nano-voltmeter (Keithley mod. 2182A) for reading the DC signal and dark current (for details see paragraph 3.4.3), modulated measurements imply, in respect to continuous irradiation conditions, the advantage of:

- High SNR discrimination of signal,
- Ability to separate and to contemporarily measure DC and AC components,
- Independence on device leakage current for a broad range (up to 0.1 mA).

This means that, under this operative condition, we can both evaluate the devices behaviour in DC irradiation (small modulation frequencies) and devices performance for AC applications.

All the setup is controlled by a computer via HPIB and RS-232 buses, which has the function of collecting data and controlling the electronic instruments. A ionization chamber designed and calibrated for photons < 100 keV was recently introduced within the setup. The aim is to always monitor the source intensity, to compare the device under test performance with the dosimetric benchmark detector and to make possible absolute dose measurements.

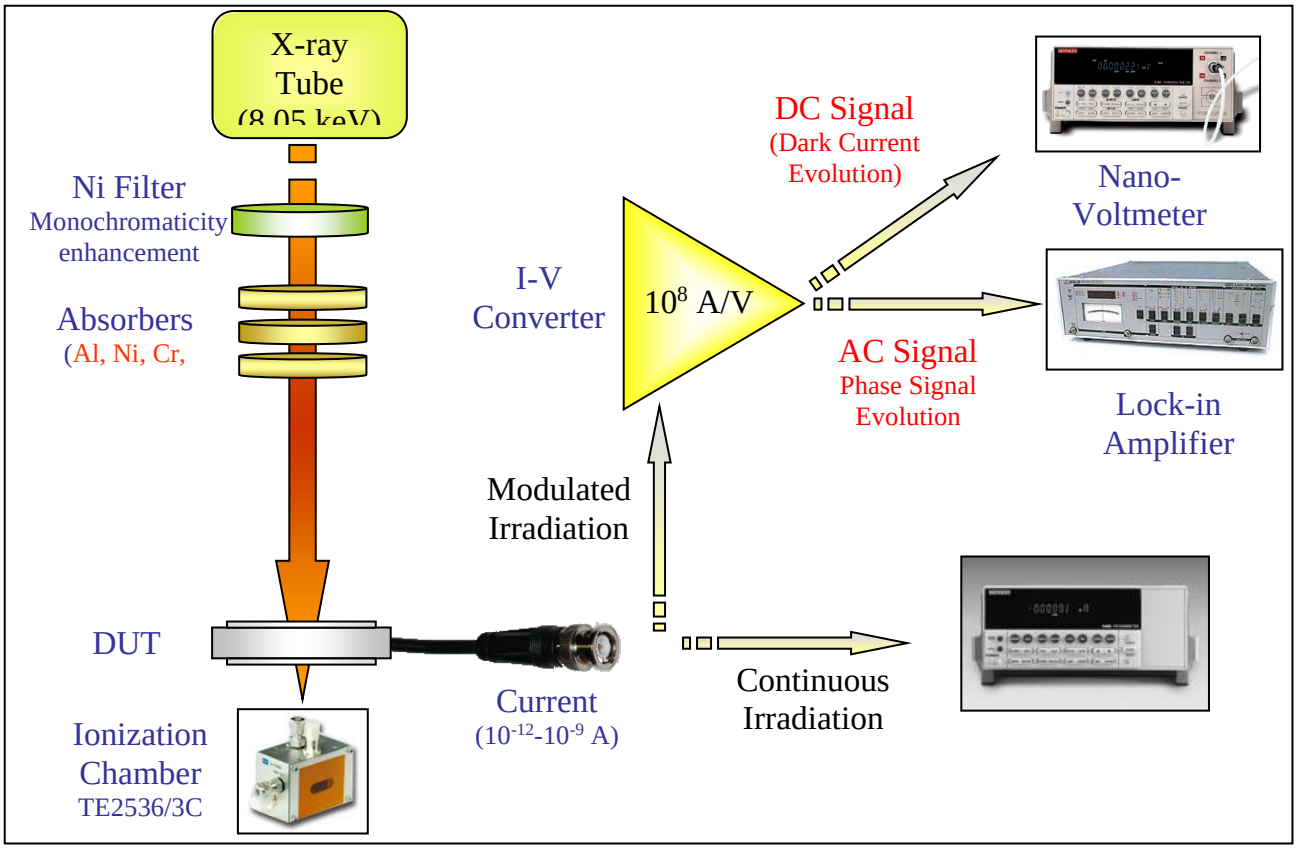

Fig. 11.

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