Nuclear Instruments and Methods in Physics Research A 809 (2016) 156–170

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Novel detectors for silicon based microdosimetry, their concepts and applications

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ARTICLE INFO

Available online 5 September 2015

*Keywords:*
SOI detectors
Microdosimetry
Proton therapy
Heavy ion therapy
RBE
Silicon on insulator

ABSTRACT

This paper presents an overview of the development of semiconductor microdosimetry and the most current (state-of-the-art) Silicon on Insulator (SOI) detectors for microdosimetry based mainly on research and development carried out at the Centre for Medical Radiation Physics (CMRP) at the University of Wollongong with collaborators over the last 18 years. In this paper every generation of CMRP SOI microdosimeters, including their fabrication, design, and electrical and charge collection characterisation are presented. A study of SOI microdosimeters in various radiation fields has demonstrated that under appropriate geometrical scaling, the response of SOI detectors with the well-known geometry of microscopically sensitive volumes will record the energy deposition spectra representative of tissue cells of an equivalent shape. This development of SOI detectors for microdosimetry with increased complexity has improved the definition of microscopic sensitive volume (SV), which is modelling the deposition of ionising energy in a biological cell, that are led from planar to 3D SOI detectors with an array of segmented microscopic 3D SVs. The monolithic $\Delta E-E$ silicon telescope, which is an alternative to the SOI silicon microdosimeter, is presented, and as an example, applications of SOI detectors and $\Delta E-E$ monolithic telescope for microdosimetery in proton therapy field and equivalent neutron dose measurements out of field are also presented. An SOI microdosimeter "bridge" with 3D SVs can derive the relative biological effectiveness (RBE) in $^{12}C$ ion radiation therapy that matches the tissue equivalent proportional counter (TEPC) quite well, but with outstanding spatial resolution. The use of SOI technology in experimental microdosimetry offers simplicity (no gas system or HV supply), high spatial resolution, low cost, high count rates, and the possibility of integrating the system onto a single device with other types of detectors.



## 1. Introduction

### 1.1. Concept and history of microdosimetry

Microdosimetry grew as a result of studying the effects of radiation on living cells because early attempts at understanding the effects of cellular radiation meant that it was essential to understand the distribution of energy at a scale comparable to the structures affected by irradiation. In the 1920s Dessauer [1] and Crowther [2] developed the earliest forms of target theory which identified discrete transfers of energy that were denoted as hits with individual ionisation, but omitting the spatial distribution severely limited the predictive capability of this early work. The late 1940s saw the development of several important concepts, especially the concept of linear energy transfer (LET). In 1952 Zirkle [3] provided the first definition of LET, although his work was closely linked to similar ideas introduced by Grey [4] and Lea [5]. The ICRU report N 16 [6] defines LET as a measure of the loss of energy per unit distance along the path of a charged particle, and also discusses some of the serious limitations the LET concept has in explaining relative biological effectiveness and the differences between types of radiation.

Kellerer and Chmelevsky [7] have investigated the effect of these limitations, including the ranges and energies over which they are important. There are several reasons why the LET concept [8] has limitations. First, it has not taken into account the track structure of ion revenant to energy deposition in micron and submicron size targets; secondly, the distribution of delta ray energy and its relationship to spatial dose distribution are not considered Second, LET is not assuming variation through the site of interest. Finally, being a non-stochastic average quantity, LET does not account for the random fluctuations in energy deposition that manifest as clusters of energy deposition and range straggling. These limitations in LET led to the formulation of a set of

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http://dx.doi.org/10.1016/j.nima.2015.08.059
0168-9002/

measurable stochastic quantities called specific energy and lineal energy that provide the fundamental basis for the field of microdosimetry. These quantities will be defined and discussed in Section 1.1.2. It is the goal of experimental regional microdosimetry to measure these quantities in well-defined volumes.

Clearly, the measurements of quantities of radiation in sites comparable in size to the cell, or even the chromosomes interaction distance are required. To realise such measurements in the early 1950s Rossi developed a low pressure proportional counter that is commonly called Rossi counter after its pioneer [9]. This was the second main experimental development in microdosimetry because it permits microdosimetric quantities at scales of the order of 1 μm to be measured. The concept of "site" involves defining volumes of interest called sites where the energy deposited by ionising radiation is considered without regard to the microscopic distribution of energy within the site. Regional microdosimetry is concerned with measuring the deposition of energy in sites, which is the basis of experimental microdosimetry [10], because intuitively, it would seem there is a link between microdosimetric experimental quantities and the observed effects of radiation on biological cells. The theory of dual radiation action, first proposed by Kellerer and Rossi in 1972 [11], seeks to establish the link between experimental radiation physics and cellular radiobiology. This theory, and the applicability of experimental microdosimetry to radiobiology, radiotherapy, radiation protection, and other applications are discussed in [12].

Prior to a discussion on the design of silicon microdosimeters and their application, the following sections will describe the principle of microdosimetry and microdosimetric quantities and previous state-of-the-art in experimental microdosimetry.

### 1.2. Basic principles and microdosimetric quantities

Formal definitions of the principal microdosimetric quantities are given by the International Commission on Radiation Units and Measurements [13]. Of primary importance is the concept of *lineal energy* $y$, which is defined as the quotient of $\varepsilon$ by $\bar{l}$, where $\varepsilon$ is the energy imparted to matter in a volume by a single energy deposition event and $\bar{l}$ is the mean chord length in that volume:

$$y = \frac{\varepsilon}{\bar{l}} \tag{1}$$

Lineal energy is commonly presented in units of keV $\mu m^{-1}$. The mean chord length in a convex volume is given by:

$$\bar{l} = \frac{4V}{S} \tag{2}$$

where $V$ is the volume and $S$ is the surface area of the body.

The measured lineal energy is subject to random fluctuations and hence is a stochastic quantity.

The probability distribution of lineal energy ($f(y)$) is a fundamental function in microdosimetry. A single set of measurements can be displayed as a frequency distribution ($f(y)$, probability of event versus event size) or as a dose distribution ($d(y)$, fraction of energy versus event size). The relationship between $f(y)$ and $d(y)$ is given by:

$$d(y) = \frac{y f(y)}{\bar{y}F} \tag{3}$$

The relationship of dose distribution reflects the fact that higher lineal energies deposit a higher dose.

The $yF$ and $yD$ have the following averages defined as

$$\overline{yF} = \int_0^\infty y f(y) dy \tag{4}$$

$$\bar{y}D = \int_0^\infty y d(y) \mathrm{d}y = \frac{1}{\bar{y}_F} \int_0^\infty y 2 f(y) \mathrm{d}y \tag{5}$$

The first moment of $f(y)$ is the frequency mean lineal energy $\bar{y}F$, whilst the second moment divided by the first is the dose mean lineal energy, $\bar{y}D$. The microdosimetric spectra $yf(y)$ vs $y$ is traditionally displayed as a log–linear plot $y^2 f(y)$ vs $lgy$ due to the wide range of lineal energy (from 0.01 to $10^3$ keV/μm) that is often observed in microdosimetric spectra. Area under microdosimetric spectra is normalised to unit.

Another important microdosimetric quantity is specific energy $z$, which is the quotient of $\varepsilon$ by the volume mass $m$; similar microdosimetric distributions and averages also apply for this quantity.

In order to present spectra in linear–log form, their normalisation must be performed correctly given a logarithmically binned histogram, as discussed in Appendix B of ICRU 36 [13].

Based on the measured lineal energy $y$, the dose equivalent ($H$) can be obtained with specified quality factor $Q$ values. The dose equivalent is defined as a measure of radiation to identify and quantify the effects of ionising radiation on health in units of Sieverts (Sv) [13].

$$H = QD \tag{6}$$

where $Q$ is the average quality factor of the radiation field and $D$ is the dose absorbed in tissue at a given point of interest. From the $d(y)$ distribution the equivalent dose can be determined by:

$$H = D \int Q(y) d(y) dy = D \int Q(y) y 2 f(y) d(log(y)), \tag{7}$$

Microdosimetry is an extremely useful tool for determining the average quality factor and equivalent dose in radiation therapy and radiation protection applications. In radiation therapy the Relative Biological Effectiveness (RBE) is obtained at higher dose levels so $r(y)$ functions are used instead of $Q(y)$ where $r(y)$ is the weighting function for 20 crypt cell regeneration in mice [14]. $r(y)$ is a known standard for the quality of clinical radiation [15] and it has been used to calculate the RBE of therapeutic neutron and proton beams at the Nice medical centre [16, 17].

### 1.3. Experimental microdosimetry using proportional counters

The approach used for microdosimetric spectra measurements is to simulate a small tissue volume using a larger gas volume, but where the energy loss of charged particles is identical in both volumes for equivalent trajectories. For a tissue sphere of diameter $d_t$, density $\rho_t$, and mass stopping power $(S/\rho)_t$ and a gas sphere with parameters $d_g$, $\rho_g$, and $(S/\rho)_g$, the required condition of equivalent energy loss is [13]:

$$\Delta Et = (S/\rho) t \rho t dt = (S/\rho) g \rho g dg = \Delta Eg \tag{8}$$

where $\Delta E_t$ and $\Delta E_g$ are the mean energy losses from the charged particle in tissue and gas. Given a gas with an atomic composition that is identical to tissue, and if the mass stopping powers are independent of density, then the design criterion becomes:

$$\rho t dt = \rho g dg \tag{9}$$

Thus by adjusting gas pressure (gas density) it is possible to mimic the micron sized sensitive volume (SV) of tissue cell with much larger gas volume that is realized in the TEPC. For example, a 2.5 cm diameter sphere filled with propane based tissue equivalent (TE) gas at 17 Torr is equivalent to a 1 μm diameter sphere of unit density material [12].