A feasibility study of a silicon solid-state microdosimeter

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I. INTRODUCTION

Solid-state silicon detectors are challenging devices for microdosimetry, mainly because they can provide sensitive zones (i.e. depletion layers) of the order of a micrometer. This type of detector can be realized by placing a tissue-equivalent converter in contact with a silicon device. A semiconductor microdosimeter is characterized by a high spatial and a good energy resolution and could be used for in-vivo measurements on a patient undergoing radiation therapy. However, it may present some limitations, such as: (i) the minimum detectable energy which is ruled by the electronic noise; (ii) radiation hardness; (iii) the geometry of the sensitive volume, which is usually parallelepiped (and not spherical like in conventional microdosimeters, such as the Rossi counter); (iv) the field-funnelling effect; (v) the non tissue-equivalence of silicon.

The use of semiconductor detectors for microdosimetry was firstly proposed in ref. [1] and further investigated in refs. [2-4]. A deep study of such a device was carried out in ref. [5].

The present work discusses the use of commercial semiconductor detectors for microdosimetry. The following items are investigated: (i) contribution of the secondary charged particles (starters) generated directly in silicon; (ii) field-funneling effect; (iii) dimensions and geometry of the depletion layer and effects due to the non tissue-equivalence of silicon.

II. FEASIBILITY STUDY

Contribution of the secondaries generated in silicon

The interaction probability of photons in silicon is fairly equivalent to that of soft-tissue (if scaled by density) above 100 keV, as is shown in Fig. 1. By contrast, tissue-equivalence does not hold for neutrons. The contribution of secondary particles generated directly in the depletion layer was studied by irradiating a PIN diode 0.5 mm thick (Hamamatsu S3509-06). The diode was not biased for minimizing the contribution of photons.

Irradiations with thermal neutrons were performed at the TAPIRO reactor (ENEA-Casaccia, Rome). The reaction rate on $^{10}$B (B is the p-dopant) was estimated to be about $2.2 \times 10^7$ s$^{-1}$ per unit thermal neutron fluence rate. Therefore, the thermal component of the irradiation field must be rather low in order to keep this contribution at negligible values.

Irradiations with monoenergetic neutrons in the range 1.0-5.0 MeV were performed at the CN Van De Graaff of the LNL. The most contributing reactions at the investigated energies were $^{28}$Si(n,$\alpha$)$^{25}$Mg and $^{28}$Si(n,p)$^{28}$Al, with threshold energies 2.75 and 4 MeV, respectively. Elastic interactions on silicon should not give rise to detectable electronic signals up to about a few MeV, because the maximum recoil energy of the silicon nuclei is about 13% of that of the impinging neutron. The detector cross section for deposited energies above 1 MeV is shown in Fig. 2.

Field-funneling effect

The field-funneling effect (FF) is due to a local distortion of the electric field in the depletion layer, induced by high-LET particles, leading to the collection of electron-hole pairs produced in the non-depleted zone. This effect leads to the dependence of the sensitive zone thickness on the particle LET. The FF was observed by irradiating a matrix of PN diodes (AMS BiCMOS 0.8 µm) with monoenergetic neutrons at the LNL. The sensitive area of each diode was 1 mm$^2$. The nominal thickness of the depletion layer of each diode, biased at 2 V, was about 2 µm. A polyethylene converter was placed in contact with the diodes during the irradiations. The spectra of the energy deposited in silicon by the recoil-protons generated in the converter are shown in Fig. 3. A shift of the deposited energy spectra was observed also when the range in Si of the recoil-protons of maximum energy was higher than the thickness of the depletion layer. This is due to the
FF which increases the thickness of the zone of charge collection up to about 12 μm and thus hinders the use of this diode matrix as a microdosimeter.

An alternative device was then considered, in collaboration with STMicroelectronics of Catania (Italy). The chosen detector was a monolithic silicon telescope [7]. This telescope consists of a ΔE and an E stage detector 1 μm and 500 μm thick, respectively. Charges are collected separately in the two stage detectors. The ΔE stage was coupled with a tissue-equivalent converter for studying its performances as a solid-state microdosimeter. A conventional preamplifier was used, leading to a detection limit of about 40 keV μm⁻¹ due to the electronic noise. It should be underlined that the capacitance of the ΔE stage is about 1 nF. Irradiations with monoenergetic neutrons were performed at the LNL and the spectra of the energy deposited in the ΔE stage are shown in Fig. 4. It should be noted that the maximum deposited energy is rather stable with the energy of the neutron beam. Therefore, the FF should be negligible and the slight variations of the maximum deposited energy may be ascribed to geometrical effects due to the track length of the recoils generated in the converter.

Monte Carlo simulations were performed with the FLUKA code to better investigate on this slight variation. The simulation code does not take into account the FF. Photons produced in the target for neutron generation were considered an alternative configuration based on a matrix of small stages. The influence of geometrical effects and the electronic noise due to the high capacitance lead to consider an alternative configuration based on a matrix of smaller stages.

The ΔE stage of the silicon monolithic telescope is an interesting device for microdosimetric applications. However, the influence of geometrical effects and the electronic noise due to the high capacitance lead to consider an alternative configuration based on a matrix of smaller stages.

REFERENCES