A Feasibility Study of a Single Event Spectrometer Based on Semiconductor Devices
REVISED VERSION

S. Agosteo(1), A. Castoldi(1), L. Castellani (3), P. Colautti(2), G. D'Angelo (1), L. De Nardo(3), A. Favalli(1), I. Lippi(3), R. Martinelli(3), G. Tornielli(3) and P. Zotto(4).

(1) Dipartimento di Ingegneria Nucleare, Politecnico di Milano, via Ponzio 34/3, 20133 Milano, Italy and INFN, Sezione di Milano, via Celoria 16, 20133 Milano, Italy.
(2) INFN, Laboratori Nazionali di Legnaro, via Romea 4, 35020 Legnaro, Italy.
(3) Dipartimento di Fisica, Università di Padova and INFN, Sezione di Padova, via Marzolo 8, 35131 Padova, Italy.
(4) Dipartimento di Fisica, Politecnico di Milano, via Ponzio 34/3, 20133 Milano, Italy and INFN, Sezione di Padova, via Marzolo 8, 35131 Padova, Italy.

<u>Running title:</u> Single Event Spectrometer

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ABSTRACT

The electronics employed around particle accelerators can be disturbed or damaged because of Single Event Effects (SEE). The most likely effect is the Single Event Upset (SEU) which may affect all memory devices. In the case of high energy accelerators, SEUs are mostly produced by secondary charged particles generated by neutron interactions. The measurement of the energy and the lineal-energy distribution of these neutron-induced charged particles was proposed. As a first approach, a commercial p-i-n photodiode was employed. This device was irradiated with thermal and monoenergetic fast neutrons. Some effects limiting the use of such detector as a SEE spectrometer were observed, giving guidelines for the design of an Application Specific Integrated Circuit (ASIC). The possibility of realizing a solid state microdosimeter by coupling the ASIC with a tissue-equivalent radiator is discussed. Moreover, the p-i-n photodiode covered with a hydrogenated plastic radiator may be employed as a proton-recoil spectrometer.

INTRODUCTION

The electronics employed in the environment of particle accelerators or in space can be disturbed or even damaged because of Single Event Effects (SEE), associated to individual ionizing particles. The most likely effect is the Single Event Upset (SEU) which may affect all kinds of memory devices (SRAM, DRAM, and FLASH memories, microprocessors, logical programmable state machines, etc.). The SEU is detected as a modification of a memory state and is recoverable by data rewriting. Memory upset is caused by the deposition of a charge higher than a given threshold, inside a device sensitive node. This charge value is dependent on both technology and device layout. In the case of high energy accelerators, SEUs are produced by secondary particles (mostly neutrons and protons) interactions in the device. The SEU rates due to neutron interactions on SRAMs were measured for the electronics foreseen for the CMS barrel muon detector(1).

In the context of that work, it was proposed to measure the energy spectrum and the lineal-energy distribution of the charged particles induced by neutrons on the silicon device. As a first approach, a commercial p-i-n photodiode was employed. This device was irradiated with thermal and monoenergetic fast neutrons at the INFN Legnaro National Laboratory (LNL, Italy). Some effects limiting the use of such detector as a SEE spectrometer were observed, giving guidelines for the design of an Application Specific Integrated Circuit (ASIC).

Another application of this detector is the realization of a solid state microdosimeter, by coupling the ASIC with a tissue-equivalent (TE) radiator. Some works giving guidelines on solid state microdosimetry can be found in the literature(2-3).

Moreover, the irradiation of the p-i-n photodiode covered with a hydrogenated plastic converter with monoenergetic neutrons suggested to study the possibility of using it as a proton-recoil spectrometer.

PRELIMINARY MEASUREMENTS

A windowless p-i-n photodiode 200 μm thick by Hamamatsu (model S3590-02), connected to a charge preamplifier (Hamamatsu H4083) was used to investigate the feasibility of a SEE spectrometer. A conventional electronic chain (i.e. a spectroscopy amplifier and an ADC) was employed for signal formation and acquisition.

The first irradiation test of the detector aimed at determining the energy distribution of secondary charged particles which may induce the SEE. Capacitive measurements were performed before irradiation to evaluate the thickness of the depletion layer against bias voltage. The minimum thickness of the depletion layer was 20 μm, obviously for zero bias voltage. This is the first factor observed which limits the utilization of the present device as a SEE spectrometer, since for SEE spectrometry (microdosimetry included), a thickness of the order of 1 μm is necessary. All the measurements described in the following refer to the photodiode not biased. The photodiode was calibrated in energy with the alpha particles emitted by a natural uranium source.

The distribution of energy deposited by the charged particles following the irradiation of the photodiode with thermal neutrons is shown in Fig. 1. The detector was placed in the irradiation cavity of the moderating structure of the thermal neutron source installed at the Van De Graaff accelerator of the LNL for BNCT studies[4]. Neutrons are generated via the ^{9}Be(d,n)^{10}B reaction and moderated by heavy-water and reactor-grade graphite. The fast neutron component (above 10 keV) is about a factor 100 lower than the thermal one. The spectrum of Fig. 1 is due to the energy deposited by the products of the reaction ^{10}B(n,α)^{7}Li, induced by thermal neutrons on the boron-dopant of the Si-device. The reaction Q-value is 2.31 MeV, shared between ^{7}Li (0.84 MeV) and the α-particle (1.47 MeV). Since the range in silicon of ^{7}Li and of the α-particle is 2.5 μm and 5 μm, respectively, and the thickness of the depletion layer is 20 μm (diode not biased), the probability of partial energy deposition is not negligible. Such events are observable in the structures at the left of the 2.31 MeV full-energy peak (Fig. 1). The spectral shape of these events is due to the distribution of the energy deposited along the tracks of the reaction products, which is not uniform. The spectrum shown in Fig. 1 confirms that SEUs are induced also by thermal neutrons, as was observed in the SRAM irradiation[(1)].

The same device (not biased) was irradiated with monoenergetic neutrons produced by bombarding a thin LiF target with proton beams at LNL. The resulting energy spectrum of the charged particles generated by 1 MeV and 4.5 MeV neutrons on silicon is shown in Fig. 2.

The spectrum referring to 1 MeV neutrons is only characterised by secondary particles depositing low energy, such as electrons produced by electromagnetic radiation (X and gamma rays) coming from the LiF target. The peak observable for 4.5 MeV neutrons is due to charged particles produced by fast neutron reactions on silicon, such as $^{28}Si(n,p)^{28}Al$ (threshold energy 4.0 MeV) and $^{28}Si(n,\alpha)^{25}Mg$ (threshold energy 2.75 MeV). This threshold-induction of SEUs was also observed during RAM irradiation[(1)].

A proton-recoil neutron spectrometer can be realised by covering the photodiode with a hydrogenated plastic radiator (e.g. polyethylene). The response functions of this detector can be measured with monoenergetic neutron beams. In this application, all the energy deposited by the recoil proton must be collected. Such a device can be biased with zero or low voltage to minimise the energy deposited by the electromagnetic radiation. As shown in Fig. 3, the charge deposited by recoil-protons is collected also in the substrate. In fact, the range of protons recoiling from neutrons of energy higher than about 1.1 MeV is larger than the thickness of the depletion layer (20 μm at zero bias voltage). This effect (field funnelling[(5)]) is due to a local distortion of the electric field of the depletion layer along the track of the high LET charge particle, causing the collection of the electron-hole pairs produced in the substrate. The maximum neutron energy which can be detected depends on the thickness of the entire photodiode. The thin depletion layer contributes to limit the detection of the energy deposited by photons and therefore to lower the minimum detectable energy of recoil protons. Fig. 3 shows the response functions of the proposed neutron spectrometer, resulting from the irradiation with monoenergetic neutron beams at the LNL.

The field funnelling effect is responsible for the dependence of the thickness of the depletion layer on the energy (and on the LET) of the secondary charged particles recoiling from a plastic radiator. This effect is of help for the realisation of a neutron spectrometer, but represent a further limit to the application of this kind of photodiode as a microdosimeter.

CONCLUSIONS

The measurements described in the present work gave guidelines for the realisation of ASICs for monitoring the SEE in the electronics exposed to radiation and for microdosimetry. A thin depletion layer and no field funnelling are the most important constraints required for such a device, currently under development.

The feasibility of a proton-recoil spectrometer basing on a p-i-n was demonstrated. Further measurements with thicker silicon detectors and with higher neutron energies will be performed in the future.

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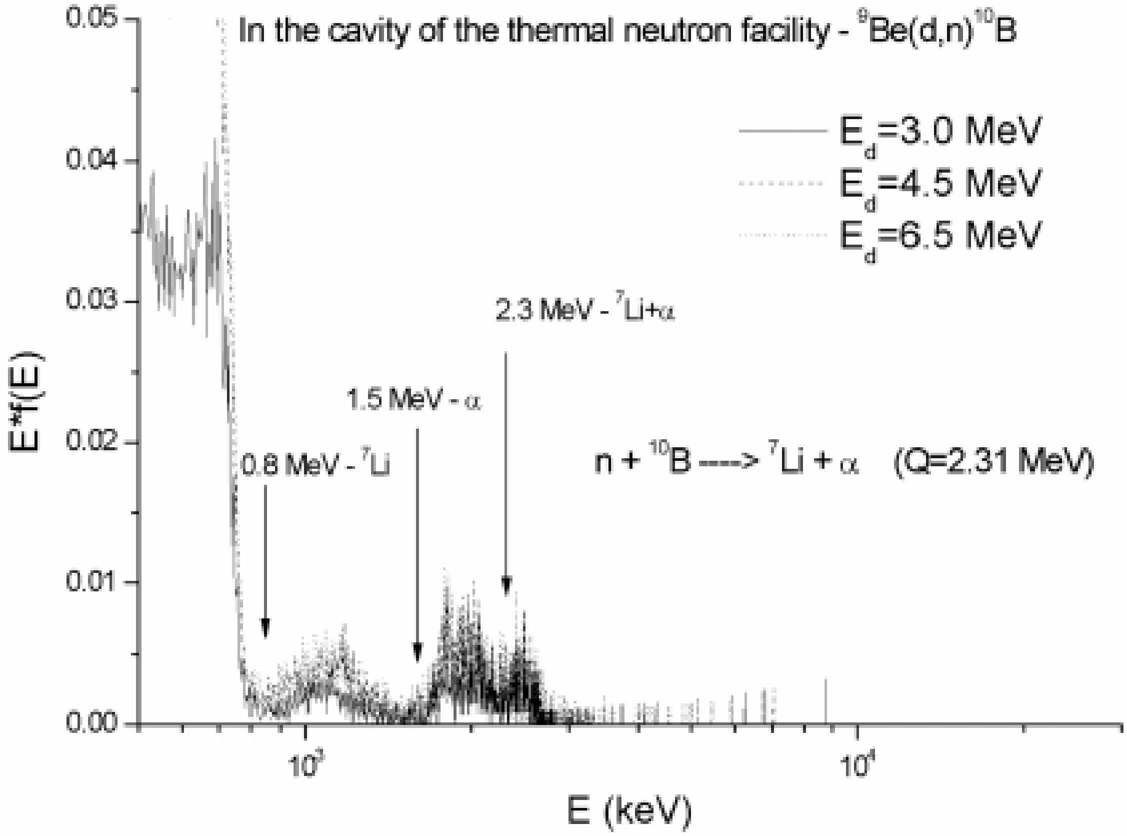

Fig.1 - Energy distribution of the charged particles produced irradiating a bare photodiode with thermal neutrons.

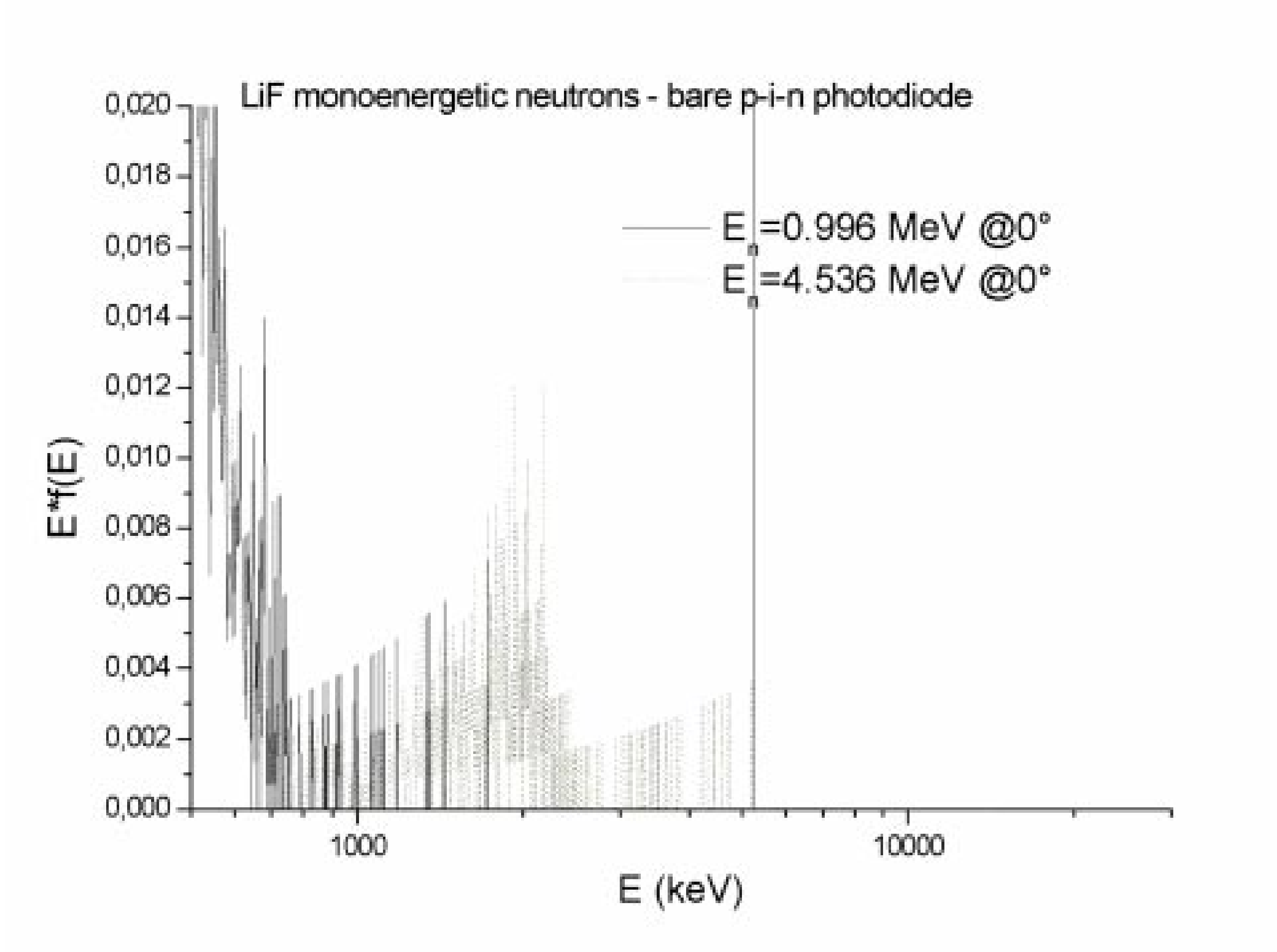

Fig. 2 - Energy distribution of the charged particles produced irradiating a bare photodiode with monoenergetic 1 MeV and 4.5 MeV neutrons.

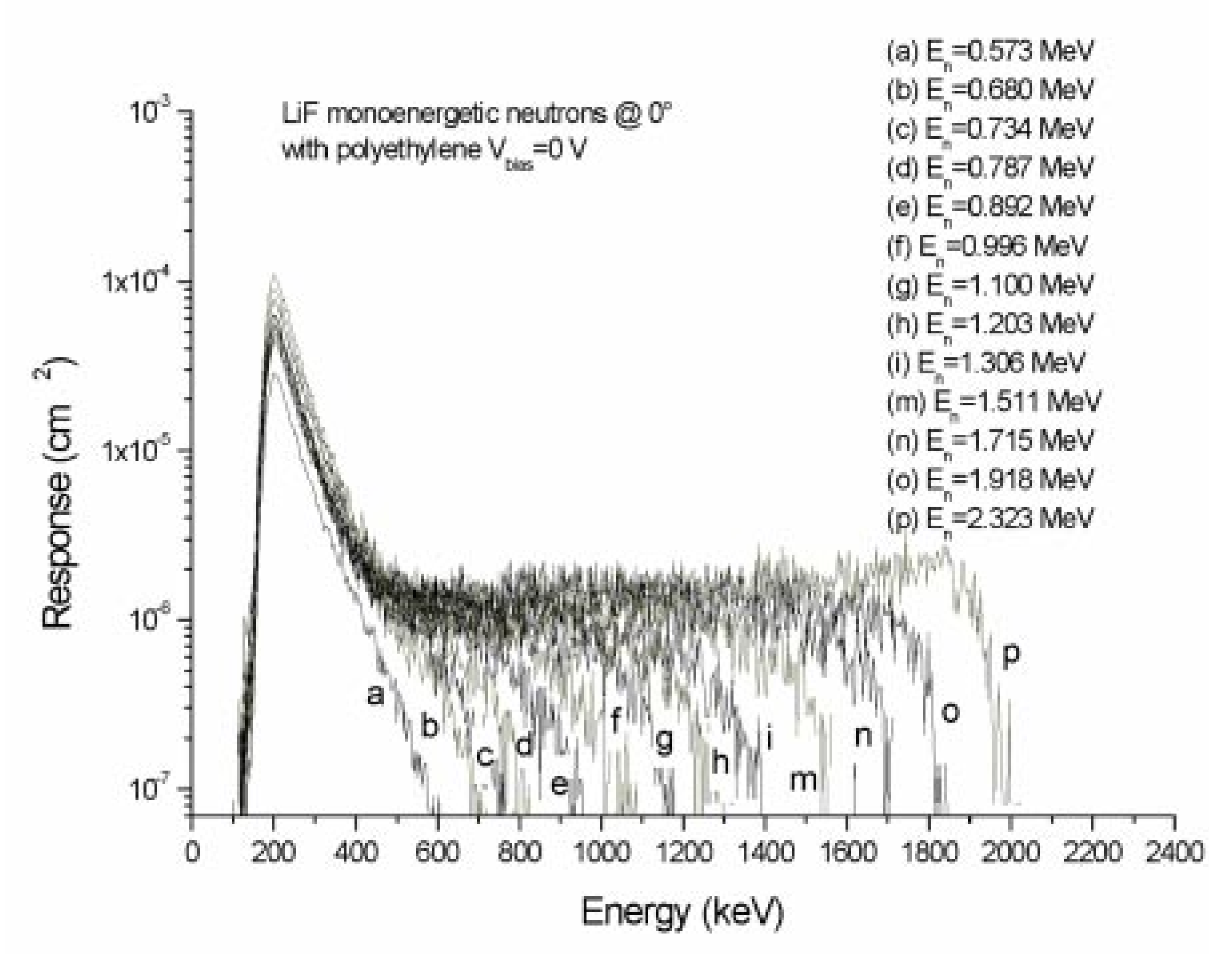

Fig. 3 –Response functions of a proton-recoil spectrometer based on a p-i-n photodiode covered with a polyethylene converter.