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The application of a SRAM chip as a novel neutron detector

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High-density, fast digital devices, like field programmable gate arrays (FPGAs), microcontrollers, and static random access memories (SRAMs), can be produced by nanotechnology. New technologies allow the design of fast and powerful devices; however, the decreasing dimensions create new problems. Even at ground level, cosmic ray particles arriving from outer space can affect digital devices and provoke single-event effects (SEEs) due to the smaller sensitive volume (SV). In general, for decreasing feature size of memory cells the expected critical charge decreases and the expected sensitivity to radiation increases.

High-density SRAM chips were used to design a fast response, highly sensitive neutron detector. We have conducted experiments with SRAMs at the DESY Research Centre in Hamburg, Germany. Memory contents (number of SEU) were recorded as a function of neutron expose time. The chips were exposed to a neutron field from an americium-beryllium neutron source (^{241}AmBe). The second experiment was accomplished in the 450 MeV electron Linac (Linac II) tunnel. Another batch of SRAMs was irradiated with ^{60}Co gamma rays to a dose of about 60 Gy, and no SEU was registered. This shows that gamma radiation has no substantial effect on the production of SEU in the SRAM. The proposed detector could be ideal for the detection of pulsed neutron radiation produced by high-energy electron linear accelerators and synchrotron facilities, which are currently in operation and planned for the near future.

Keywords: Single-event effect; Single-event upset; Static random access memory; Nanotechnology; Beam loss Monitoring system

1. Introduction

Bremsstrahlung gamma radiation and photoneutrons are generated during the operation of high-energy linear accelerators [1, 2]. This parasitic radiation could run the risk of radiation damage to electronic systems placed in the neighbourhood of the accelerator.

One can use different types of detectors to monitor the neutron and gamma radiation level and deliver prompt warnings when the radiation exceeds a preset alarm level [3].

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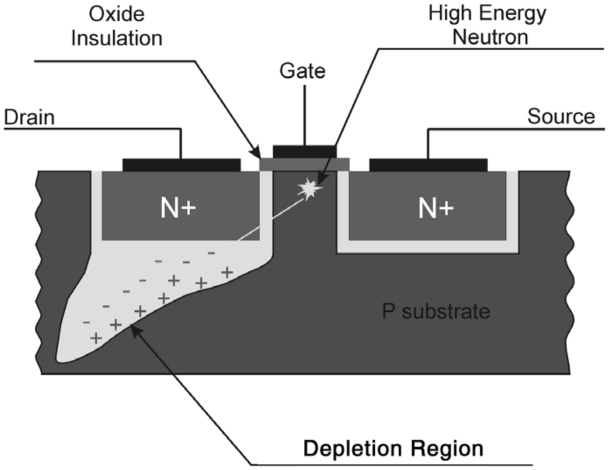

Figure 1. Ionization of a MOS structure as an effect of interaction with a particle.

Large varieties of presently available sensors, such as photomultipliers, Compton diodes, ionization chambers, scintillation counters, aluminium cathode electron multipliers, and PIN diodes, are used for the detection of gamma radiation [3]. On the other hand, no neutron detector with a fast response time and an interface capability to computerized radiation monitoring is available. The primary criterion of a neutron detector for a pulsed radiation field produced by a high-energy accelerator, such as the newly installed X-Ray Free-Electron Laser at DESY [1, 4], is a fast response time. Common BF3 chamber-based neutron detectors suffer from long response times and pulse pile-up effects, and therefore could not be used to detect pulsed neutrons in real time.

Static random access memories (SRAMs), susceptible to neutron-induced single-event upsets (SEUs), are selectively sensitive to neutrons and give practically no gamma response. Hence, these devices are good candidates for neutron detection within a radiation field contaminated with a strong gamma background [1]. The SEUs play the most important role in neutron detection. They are induced by heavy charged particles (i.e. alpha particles, recoil nuclei) which lose their energy in the interface region of the metal oxide semiconductor (MOS) structures (figure 1) of memory cells [1, 5].

Dynamic random access memories (DRAMs), previously used by other investigators for neutron detection, require frequent refreshing of the memory content [6]. On the other hand, the present device runs without memory refreshment. This paper highlights a novel, inexpensive and reliable neutron detector based on the SEUs of SRAM chips.

The design of a reliable refreshing circuit, which is often intended to be used in a high-radiation (neutrons and gamma rays) environment, makes the device more complicated and therefore less reliable. Most research was done using densely ionizing particles like alpha particles or protons [7]. The number of generated errors in the memory increases with time and depends on the neutron dose. The SRAM-based neutron sensor described in this paper possesses a linear response, and hence could be used as a neutron counter. This application requires the use of the high-density memory in order to increase the sensitivity.

2. Neutrons produced in a Linac environment

The X-FEL X-Ray Free Electron Laser operating in the X-ray regime uses a 20 GeV accelerated electron beam [8, 9]. Bremsstrahlung photons and photoneutrons are produced during the operation of such a high-energy electron Linac [17]. The first type of radiation effects concerns accidental electron beam losses. The beam energy is lost and thereby an intense field of photoneutrons and bremsstrahlung gamma rays are produced [4, 10].

The second type of effect concerns unavoidable beam losses, which are localized in the collimator, limiting the beam profile [11]. Radiation in the accelerator tunnel is produced when of the electron beam interacts with high-Z materials, such as collimators or scrapers. High-energy neutrons are produced when the energy of the incident electron beam exceeds the threshold limit [10]. Systems capable of detecting a sudden beam loss in the accelerator facilities are urgently required by the accelerator user community [12].

3. The influence of radiation on electronic devices

The two main groups of radiation effects on SRAM devices can be classified as cumulative effects (CEs) and single-event effects (SEEs).

SEEs play a more important role when considering the beam loss phenomenon in the high-energy accelerator environment. Static SEEs, called single-event upsets (SEUs), could be induced only by charged particles (alpha particles or recoil nuclei) losing their entire energy near the interface region in MOS structures of the memory cells [5–7, 13] and affect random access memories (SRAMs and DRAMs), registers, buffers and programmable devices. Moreover, SEUs could be observed in SRAM devices placed in the neutron environment because of inelastic and elastic nuclear reactions, e.g. recoil reactions of proton or alpha particles, which can deposit enough energy locally [1]. SEUs occur mainly in the nearest surroundings of the sensitive area of memory cells due to the shallow depth penetration of neutrons. Figure 1 depicts the SEU phenomenon in a MOS structure induced by neutrons.

Primary and secondary ionizing particles create electron–hole pairs in a silicon device [7, 16]. Due to the existence of strong electric fields, the charge carries are moved and collected near the MOS electrodes. The charge accumulated near the MOS drain could result in a single memory cell or a flip–flop state change [13]. An SEU affecting a standard 6 T SRAM cell is shown in figure 2. In the picture above transistors T_1 and T_4 are conducting, therefore the output data line is equivalent to logic state ‘1’ and the complementary data line is ‘0’. When the particle interacts with the sensitive area of transistor T_3 the state of the flip–flop will change and the state of the data lines will change, respectively: the data line is equal to ‘0’ and the complementary data line equal to ‘1’ (on the assumption that the pass transistors are conducting).

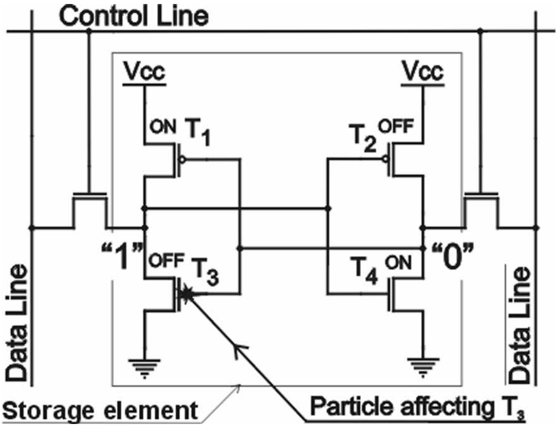

Figure 2. SEU generated in a standard 6 T SRAM cell.

The deposition of energy should occur in the silicon volume of a collecting node, which is called the sensitive volume (SV) [5]. According to current publications on the subject, deactivated transistors (e.g. T_2, T_3) could be changed mainly by charged particle interaction [14]. The SEU, also called a 'soft error', is a non-destructive phenomenon. The initial state of the memory can be achieved by rewriting its contents.

Long-lived, cumulative effects are caused by electrons, neutrons, protons, alpha particles, gamma rays and heavy ions. Energy deposited by gamma radiation and charged particles cause ionization in the material. Because of these changes, the excitation, charge transport, bonding, and decomposition properties of the material are modified, and this has an influence on the parameters of the device. This phenomenon is called the total ionizing dose (TID) [1].

SRAM devices subjected to gamma radiation could be damaged because of the charge integration near the Si–SiO_2 interface in metal oxide semiconductor (MOS) structures. The shift in the threshold voltage and increase in the leakage current are indicators of the TID effect. This is a detrimental effect and plays a crucial role in the SRAM's lifetime [4].

4. Results

Three experiments with SRAM were carried out at the DESY Research Centre in Hamburg. During the first stage, the memory sensor was irradiated with an americium–beryllium (^{241}Am/Be) neutron source [2].

The second experiment was accomplished in the Linac II tunnel. The chip was connected to a PC so the number of induced errors was registered in real time. The final measurement was carried out using a gamma source in order to prove that gamma radiation in the Linac environment will impose minimum effects to create SEUs. A 128 kb SRAM, manufactured by Samsung, was used. The memory was powered by a 5 V supply.

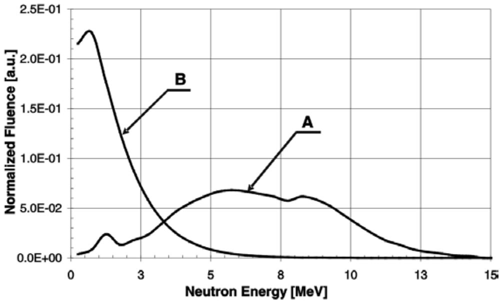

Figure 3. Spectrum of the ^{241}AmBe neutron source.

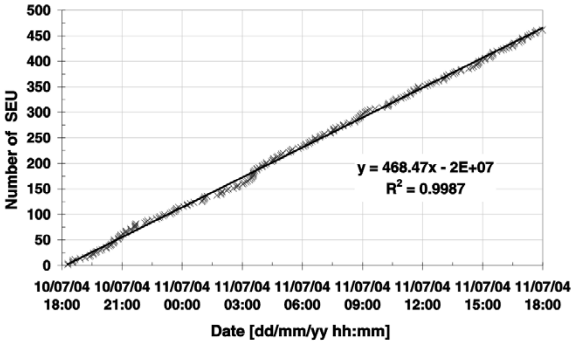

Figure 4. SEUs induced in the SRAM memory irradiated with a ^{241}AmBe neutron source.

4.1. *Neutron exposure with ^{241}AmBe source*

For the first measurement, a ^{241}AmBe neutron source was used. The energy spectrum [2] of the neutron source is shown in figure 3.

The curve A represents the ^{241}AmBe source spectrum, and B is the photoneutron spectrum of Linac II. The area under both spectra (A and B) was normalized to unity. The distance between the active part of the memory and the source was 10 mm. The memory was connected to a PC to facilitate reading and writing of its contents in real time. A bit pattern was written in the memory before irradiation. The contents of the device were read every minute and compared with the reference. An SEU was registered every time the contents of the irradiated memory differed from the reference value. The memory chip was irradiated for 24 hours. The memory contents changed in a given time frame depending on the absorbed neutron dose in the chip, as shown in figure 4. Evidently, the computer was not subjected to any radiation exposure, as it was installed in an adjacent room and separated by a thick concrete shielding wall. The figure shows a linear relationship between SEUs induced in the memory and time. The neutron source used during the experiment provided a constant number of neutrons, therefore one can conclude that the number of

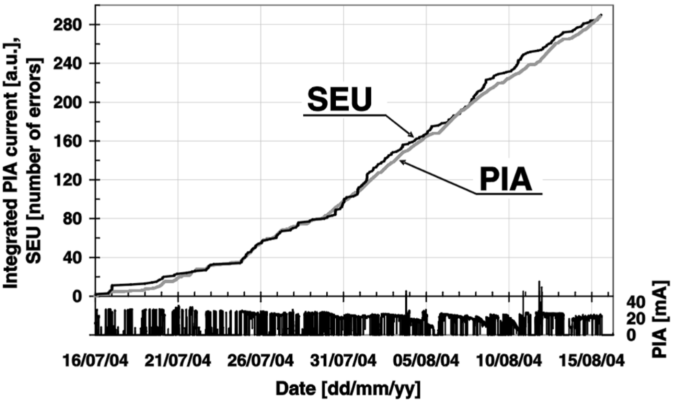

Figure 5. SEUs induced in the SRAM and the integrated PIA current shown as functions of elapsed time.

generated SEUs is dependent on the absorbed dose of radiation. The neutron fluence for 24 hours was calculated to be 2.3×10^{10} neutron $\cdot$ cm^{-2}. This corresponds to 480 upsets (SEUs). For one hour (9.7×10^{8} neutron $\cdot$ cm^{-2}) the number of upsets (SEU) was equal to 20.

4.2. *On-line measurements in Linac II*

The second experiment was carried out in the linear accelerator Linac II tunnel [15]. The main source of neutrons and gamma rays in Linac II is the electron-to-positron converter. The photoneutron spectrum of Linac II is well known [2] and depicted in figure 3. The distance between the memory and the electron-to-positron converter was about 18 m. The temperature of the memory was constant during the experiment and equal to 37°C.

The curve (figure 5) represents the growing number of SEUs induced by neutrons present in the Linac II chamber during 48 hours of accelerator operation.

The curve (figure 5) is not linear, as compared with the curve for the SRAM irradiated with the ^{241}AmBe source (figure 4). Moreover, the radiation dose absorbed in the memory was not constant. This was dependent on the accelerator's operating conditions. There was no radiation sensor available; this could have recorded the relevant radiation data in real time. Therefore, it was impossible to precisely estimate the radiation dose absorbed by the memory chip. However, we used the positron intensity accumulator (PIA) current (figure 5) for scaling the radiation dose during the experiment.

Evidently, one can see an increase in SEU events as a function of PIA current. However, it is crucial to calibrate the SRAM chip in order to realize an efficient neutron dosimeter.

4.3. *Gamma irradiation using a ^{60}Co source*

No SEU was observed while the memory was irradiated with gamma radiation. A ^{60}Co gamma source (average gamma energy: 1.3 MeV) was used. The memory chip was irradiated to 600 Gy in 120 hours. This high gamma radiation seems to have produced practically no SEUs. However, it might be detrimental for the function of the memory when it exceeds the safe level because of the TID effect. Therefore, the lifetime of SRAMs must be estimated.

5. Conclusions

This paper presents a novel technique to design a reliable, user-friendly and low-cost neutron detector. Earlier work concerned mainly the application of dynamic memories (DRAM) that require refreshing. The design of a dependable refreshing circuit, which is often intended to be used in a high-radiation environment (neutrons and gamma rays), makes a device more complicated and therefore less reliable. Most research was done with ionizing particles like alpha particles or protons [6].

The number of SEUs in the memory increases with time and depends on the neutron dose. Furthermore, an SEU is non-destructive; the memory contents can be recovered by rewriting. The proposed SRAM-based neutron sensor reveals good linear behaviour and can serve as a neutron detector. In order to increase the sensitivity, such a detector requires a high-density memory. However, the memory characteristic may vary due to different manufacturing conditions [14], and hence the calibration of individual memory chips becomes vitally important.

The proposed sensor ensures a fast response. The number of SEUs is independent of the gamma dose. However, as the TID effect is detrimental to memory devices, the lifetime of the detector must be estimated for its future applications. SRAM memories, because of single-event upsets, are selectively sensitive to neutrons, and hence are good candidates for applications in a mixed neutron–gamma radiation field.

It is of overriding importance to enhance the sensitivity of the SRAM memory to SEUs, thereby decreasing the lowest detection level of the neutron and gamma dose. Further research concerning improvements of SRAM sensor sensitivity is still in progress in our institutions.

The outcome of the present research reveals that modern high-density memory chips, exclusively manufactured using nanotechnology, are more immune to SEUs, because it is possible to implement error-correction code within the chip. These radiation-immune microchips are not suitable for neutron detection. However, they are invaluable for the construction of other vital parts of the electronic circuitry, such as digital signal processor and microcontroller-based systems.

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