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Application and development of ion-source technology for radiation-effects testing of electronics

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ABSTRACT

Studies of heavy-ion induced single event effect (SEE) on space electronics are necessary to verify the operation of the components in the harsh radiation environment. These studies are conducted by using high-energy heavy-ion beams to simulate the radiation effects in space. The ion beams are accelerated as so-called ion cocktails, containing several ion beam species with similar mass-to-charge ratio, covering a wide range of linear energy transfer (LET) values also present in space. The use of cocktails enables fast switching between beam species during testing. Production of these high-energy ion cocktails poses challenging requirements to the ion sources because in most laboratories reaching the necessary beam energies requires very high charge state ions. There are two main technologies producing these beams: The electron beam ion source EBIS and the electron cyclotron resonance ion source ECRIS. The EBIS is most suitable for pulsed accelerators, while ECRIS is most suitable for use with cyclotrons, which are the most common accelerators used in these applications.

At the Accelerator Laboratory of the University of Jyväskylä (JYFL), radiation effects testing is currently performed using a K130 cyclotron and a 14 GHz ECRIS at a beam energy of 9.3 MeV/u. A new 18 GHz ECRIS, pushing the limits of the normal conducting ECR technology is under development at JYFL. The performances of existing 18 GHz ion sources have been compared, and based on this analysis, a 16.2 MeV/u beam cocktail with 1999 MeV $^{126}Xe^{44+}$ being the most challenging component to has been chosen for development at JYFL. The properties of the suggested beam cocktail are introduced and discussed.

1. Introduction

The harsh radiation environment in space poses a serious threat on the operation of electronic devices and thus the radiation effects on the components to be used in space need to be studied on ground in order to estimate the robustness of the components. Data from the tests are required when selecting components for complete systems. The space radiation environment threatens the operation of solid-state microelectronic devices in spacecraft via two effects, which can be divided into main categories. Cumulative radiation effects, such as total ionizing dose (TID) and displacement damage (DD), can cause undesirable drifts in device characteristics, such as increased leakage currents or threshold voltage shifts. So-called single-event effects (SEE) can cause immediate changes in the device operation, some of them destructive and some non-destructive. Non-destructive soft errors cause erroneous circuit behaviour, such as bit flips in memory elements (single event upsets, SEU) or transient pulses in logic (single event transients, SET). SEE effects also include destructive phenomena, such as single event gate rupture (SEGR) that typically occur in power transistors [1].

When radiation, either high energy particles or photons, passes through electronic components the interactions with the matter cause ionization resulting in generation of electron–hole pairs. Because the average energy required to produce a single electron–hole pair in silicon is roughly 3.6 eV [2], the excess charge induced by radiation can be estimated from the deposited energy. For particle radiation the deposited ionization energy can be estimated by using the electronic energy loss or electronic stopping force (dE/dx) of the particle. Typically this is given in units of MeV·cm^2/mg. For most cases, electronic stopping force can be considered to be equal to the deposited energy i.e. linear energy transfer (LET). If the LET value for the particle is low enough, less than a threshold value LET_{th}, specific for each component, no SEE are observed and only cumulative effects are of concern. At LET values

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higher than the threshold the cross-section for SEE increases as a function of the LET until a saturation cross-section (σ_{sat}) is reached. See example in Fig. 1 for results of SEU test of a memory component. Testing for accumulated effects and SEE are normally done separately. The tests for accumulated ionizing dose can be done using, for example gamma rays from a ^{60}Co source thus removing the requirement for complicated equipment. The SEE tests, on the other hand, can only be performed using large-scale accelerator facilities because of the very high particle energies required. In the following chapters of this paper, the SEE testing procedure and the requirements on the accelerator facilities are discussed and in the final chapter the facilities at Jyväskylä are described.

2. Requirements for accelerator facilities

In order to estimate the component's soft error rate in the intended environment, it is necessary to measure the cross-sections covering the LETs present in the radiation environment or at least covering wide enough range of LETs to make a Weibull fit [4] to the measured failure data to enable sufficiently accurate extra- and interpolation. To fullfill this condition for most of the components to be tested the range of LETs available should span from 2 to 60 MeV·cm^2/mg [5]. While in space the particle energies can be so high that they penetrate the satellite body and the electronic components, in radiation effects testing the energy and range of particles is always more limited. Therefore the components are usually prepared in various ways in order for the ions to reach the sensitive region. Also, relatively narrow energy spectrum of particles at the active region of the component is preferred in order to facilitate the analysis. The preparation may include only the removal of the protective case of the component (delidding) or both delidding and thinning of the silicon substrate, which is necessary if the irradiation must be done through the substrate. This is the case in most modern components due to inversely mounted substrate or use of lead frames on top of the active silicon region [6]. The substrate can be milled down to a thickness of 50 μm depending on the size of the chip, which sets the requirement for the range of particles in these cases. Especially the substrates of large CPUs can not be milled very thin without damaging the component and therefore it is necessary to use highly penetrating particles [7]. Even in the case of irradiation from the front the range of particles should be at least 40 μm according to European Space Agency (ESA) specification [5]. The particle fluxes in SEE irradiation need to be dense enough to determine the cross-section of the events with sufficient accuracy in a reasonable time. The ESA specification requires fluxes adjustable from 10 to 10^5 particles/cm^2/s [5], but also greater fluxes are sometimes desired.

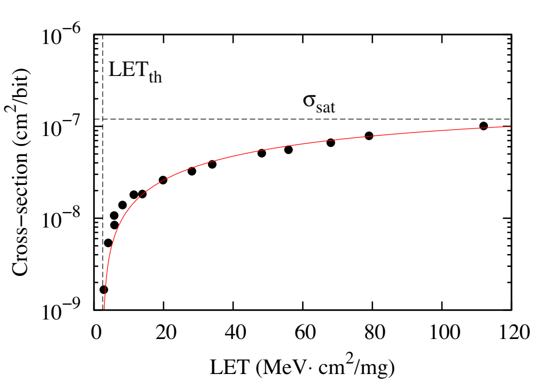

Fig. 1. SEU response of a static random-access memory (SRAM) based reference SEU monitor to ionizing radiation (Data from reference [3]). Solid points denote the measured (SEU) cross-section and the solid curve a Weibull fit to the data. The LET threshold and saturation cross-section deduced from the fit are indicated with dashed lines.

To reach the LET and range requirements the SEE tests have to be performed in large-scale accelerator facilities reaching adequate particle energies. In most cases, circular particle accelerators are used to provide the high energy particle or more specifically ion beams. In circular machines, where the maximum energy of heavy ions is limited by the radius and maximum magnetic flux density B of the machine, the maximum ion energy is given by $E = KQ^2/m$, where Q is the ion charge state, m is the ion mass and K is an accelerator specific constant. Due to the quadratic dependence on Q it is more economical to obtain high energies by accelerating high-charge-state beams (large Q) rather than by building large accelerators (large K). Therefore there is a strong demand for ion sources producing high-charge-state beams. While the development of the accelerator facilities is mainly driven by needs of fundamental research on nuclear and particle physics, these facilities are also suitable for SEE testing. Because a range of LETs is needed for testing each component it is beneficial to be able to change between ion beams rather quickly. To make it possible, the ion species used for irradiation are usually selected to form so-called ion cocktails, which contain ions with similar m/q ratios, where $q = Qe$ is the ion charge. In most accelerator laboratories the resolving power of beamline dipole magnets is about 100, which allows transport of ions with m/q ratios within 1%. This allows the ions to propagate through the beam lines of the accelerator facility with constant settings while the separation of the ions happens by tuning the accelerator radiofrequency and/or magnetic flux density. The beam delivered to the devices under test contains only one ion species at the time. In some cases the m/q ratios of cocktails are within a few percent of each other, which means that slight tuning of the beamline ion-optics is needed when changing between ions.

SEE testing facilities exist all around the world, for example in Brookhaven National Laboratory (BNL), Lawrence Berkeley National Laboratory (LBNL) and Texas A&M University (TAMU) Cyclotron Institute in the USA; Cyclotron Research Center at Louvain-la-Neuve (UCL), Belgium, Grand Accelerateur National D'Ions Lourds (GANIL) in Caen, France and University of Jyväskylä Accelerator Laboratory (JYFL) in Finland [1]. All of these facilities have their advantages and disadvantages and the suitability of each facility for a certain test campaign should be evaluated based on requirements for LET values, ion ranges, cost and convenience.

3. Requirements for ion sources

The production of high-charge-state cocktails poses demanding requirements for the ion sources used to produce the beams. There are two well established ion source types which are capable of meeting these requirements: The electron beam ion source EBIS [8] and the electron cyclotron resonance ion source ECRIS [9].

In an EBIS the highly charged ions are produced by step-wise ionization in an electrostatic trap by electron impact ionization in a high-density electron beam, which is compressed using a solenoidal magnetic field, typically realized with superconducting coils. The positive ions are trapped radially by the space charge of the electron beam propagating through the trap and axially by potentials on drift-tube electrodes around the trap. The operation of the EBIS is periodic. At the start of the operational cycle the trap is loaded with $Q = 1$ ions using external so-called primary ions sources [10]. These ions are then further ionized in the trap. The EBIS produces a relatively narrow spectrum of charge states, which is controlled primarily by adjusting the trapping time and the energy of the electron beam. At the end of the ionization period the beam pulse is formed by emptying the trap axially by controlling the drift-tube potentials. While the EBIS can also be operated

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