SAND2011-3022C

Influence of beam conditions and energy for SEE testing

V. Ferlet-Cavrois, J. R. Schwank, S. Liu, M. Muschitiello, C. Poivey, A. Zadeh, R. Harboe-Sorensen, G. Santin, P. Truscott, B. Nickson, A. Menicucci, M. Poizat, C. Binois, T. Beutier, D. Peyre, A. Carvalho, R. Mangeret, S. Metzger, S. Höffgen, D. Schardt, A. Virtanen, H. Kettunen, A. Javanainen, G. Berger, B. Piquet, J.-C. Foy, M. Zafrani, F. Bezerra, R. Ecoffet

***Abstract*—The effects of heavy-ion test conditions and beam energy on device response are investigated with several test vehicles, SRAM and power MOSFETs. Nuclear interactions dominate the device response when measuring rare events at high fluence.**

***Index Terms*— Heavy Ions, Single Event Effects, ion energy**

I. Introduction

A number of heavy-ion test conditions impact DUT response and hence, the results (conclusions) of the test. For example, one may obtain different results if the testing is performed in air or in vacuum. In addition, scattering of the beam with materials in its path, including degraders and/or detectors, and DUT overlayers, can induce significant amounts of energy straggle causing a large distribution in ion energy and effective LET in the device sensitive volume. The complete energy distribution needs to be taken into account to analyse the device response under irradiation. In the case of power MOSFETs, it has been shown that the SEB voltage is linked to the ion specie, rather than just the ion LET []. Such an effect can be explained by high collected charge events when testing is performed at high energy, coming from nuclear interactions in all materials encountered in the beam path before reaching the device sensitive volume. In the case of SRAMs and digital ICs, the device sensitivity in the vicinity of the threshold LET has also been shown to depend on the beam energy and test conditions [].

In this work, the effects of heavy-ion test conditions on device hardness are investigated. These include the effects of beam energy, performing irradiations in air or vacuum, and the effects of shadowing. The measurement of “rare” events, SEUs in SRAM below the threshold LET and destructive events in power MOSFET are analysed as a function of beam energy. This work has important implications for hardness assurance testing for space environments.

Manuscript received April 29, 2011. This work was supported by the ESA Technical Assessment program and the ESA-ESTEC 21985/08/NL/AT contract. The part of this work performed at Sandia National Laboratories was supported by the Defense Threat Reduction Agency and the U.S. Department of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy’s National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Véronique Ferlet-Cavrois, Michele Muschitiello Christian Poivey, Ali Zadeh, Reno Harboe-Sørensen, Giovanni Santin, Bob Nickson, Alessandra Menicucci, Marc Poizat are with the European Space Agency, ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands. (email: Veronique.Ferlet-Cavrois@esa.int).

James R. Schwank is with Sandia National Laboratories, MS-1083, Albuquerque, NM 87185-1083 USA.

Sandra Liu and Max Zafrani are with International Rectifier Corporation, 1521 Grand Avenue, El Segundo, CA 90245, USA.

Pete Truscott is with QinetiQ, Dept. Aerospace Division, Farnborough, Hampshire GU140LX, UK.

Christian Binois, Thierry Beutier, Daniel Peyre, Aminata Carvalho and Renaud Mangeret are with EADS Astrium, 1 bd Jean Moulin, 78990 Elancourt, France.

Stefan Metzger and Stefan Höffgen are with Fraunhofer INT, Appelsgarten 2, 53879 Euskirchen, Germany.

Dieter Schardt is with GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany.

Ari Virtanen, Heikki Kettunen, Arto Javanainen are with the University of Jyväskylä, Department of Physics, Accelerator Laboratory, Survontie 9, FI-40014 Jyväskylä, Finland.

Guy Berger is with the Université Catholique de Louvain, Chemin du Cyclotron, B-1348 Louvain-la-Neuve, Belgium. Louvain-la-Neuve, Belgium.

Bruno Piquet and Jean-Claude Foy are with GANIL, Grand Accélérateur National d’Ions Lourds, Boulevard Henri Becquerel, 14076 Caen, France.

Françoise Bezerra and Robert Ecoffet are with CNES, 18 avenue Edouard Belin, 31401 Toulouse Cedex 9, France.

II. Description of Experiments

Several different facilities were used in this work, from low to high energies: UCL [], RADEF [], TAMU [], GANIL [] and GSI []. For energies below 10 MeV/a (UCL with the low energy cocktail and RADEF at 9.3 MeV/a), the majority of the tests were performed in vacuum. However, some of the RADEF irradiations were also performed in air to compare the amount of charge collection between irradiations performed in air and vacuum. At higher energies (TAMU, GANIL, GSI), all tests were performed in air. At TAMU, the 25 MeV/a cocktail was used, without degraders, and with the devices placed a few centimeters from the beam output window. At GANIL, one ion was used (^{129}Xe). The beam energy and LET were varied by using different aluminum degrader and air thicknesses. At GSI, tests were performed in air using one ion, ^{64}Ni. The primary energy of the ^{64}Ni beam was tuned from 100 MeV/a to 1000 MeV/a to vary the ion LET. The devices were placed about 1 meter from the output window.

Several test vehicles were used to analyze the effect of the beam energy. The first test vehicle is referred to as the “Reference SEU Monitor” and has been used by several facilities in Europe to monitor beam dosimetry and uniformity

[1, 2]. Using this test vehicle, static SEU measurements at RADEF and TAMU (from [3]), were compared with measurements performed at very high energies at GSI. For each beam condition, two SEU measurements were successively performed either with checkerboard or complementary checkerboard patterns to verify the consistency of the SEU monitor response.

The second type of test vehicle used in this study was fabricated using a modified version of an International Rectifier 200-V radiation hardened power MOSFET (IRHC57230SE). The commercial version of the IRHC57230SE does not exhibit SEB up to its rated breakdown voltage 200-V, and is not sensitive to SEGR at low gate biases. The modified version of the device (57230SE) was designed to be SEB sensitive. More details about the engineered device (57230SE) can be found in [4].

The third type of test vehicle, the MM2K, is also a 200-V power MOSFET, but fabricated by STMicroelectronics. The MM2K transistor is a COTS component. It was used in this study for charge collection measurements.

The last test vehicle used in this study is a Silicon Surface Barrier Detector (SSBD) fabricated by Canberra. It is a fully-depleted PIN diode with a 300-µm thick intrinsic silicon depletion region. It was biased at 60 V. It was used to characterize the beam energy characteristics by measuring the charge deposited in the fully depleted intrinsic region.

III. Experimental Results

A. *Reference SEU Monitor*

Fig. 1 compares the SEU cross-section of the reference SEU monitor at RADEF (9.3 MeV/a), TAMU (25 MeV/a) and GSI (100-1000 MeV/a). At GSI, all data were taken at normal incidence. The beam LET was varied by tuning the beam primary energy. At TAMU and RADEF, data were taken at either normal incidence (full symbols) or at 45° and 60° angles (open symbols). Above the threshold LET, at about 5 MeV-cm^2/mg, the SEU cross section is approximately the same for the different facilities, indicating consistent dosimetry measurements between the facilities. However, at low LETs there is a strong discrepancy in the measured SEU cross-sections depending on the beam energy. For example, at 1.8 MeV-cm^2/mg, the SEU cross-section is 2×10^{-11} cm^2/bit at RADEF with 9.3 MeV/a Nitrogen; it increases by a factor 5 with 25 MeV/a Neon at TAMU; but then decreases by more than two orders of magnitude at very high energies, 500 MeV/a Ni at GSI.

Some energy effects have been shown previously in SRAM test vehicles [5]. P. E. Dodd et al. [6] showed a clear increase in the SEU cross-section in a 0.35 µm design-hardened bulk SRAM from low energies (< 10 MeV/a at BNL) to high energies (~15-40 MeV/a at TAMU). S. Duzellier et al. [7] showed a significant decrease of the SEU cross-section in a 0.8 µm bulk 256-kbit SRAM (HM65656 – MATRA MHS) from low energies (<10 MeV/a) to very high energies (250-400 MeV/a). These previously published data are consistent with our measurements despite the different generations and technologies of the SRAM test vehicles. However, it is the first time that energy effects are shown in a single test vehicle, with a clear identification of the worst-case energies in the range of 10's MeV/a.

Another point of interest concerns the determination of the threshold LET. It is clear from Fig. 1 that the cross-section values around the threshold LET tends to decrease at very high energy. These aspects are further developed in [8] with additional very high energy data. Finally, the lower cross-section at very high energy, below or around threshold LET has been observed as well in Ref. [7] and attributed to the larger ion track structure at very high energies [9]. This will be simulated with Geant4 in the final paper.

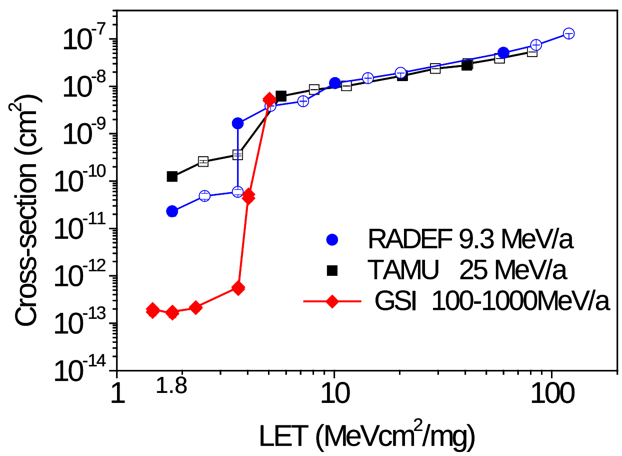

Fig. 1. Cross-section (in cm^2/bit) of the SEU monitor versus heavy ion LET at three facilities, RADEF (9.3 MeV/a cocktail), TAMU (25 MeV/a cocktail), GSI (Ni-64, primary energy varying between 100 and 1000 MeV/a). The full and open symbols at RADEF and TAMU respectively correspond to normal incidence and tilted angles (45° and 60°). AT GSI all data are in normal incidence; the LET varies with the beam primary energy, successively at 1000-500-300-150-130-100 MeV/a.

B. *IR57230SE engineering parts*

Fig. 2 summarizes single-event-burnout (SEB) voltage measurements of the engineering device, 572301SE, as a function of the incident Xenon beam energy. For each beam condition, the drain voltage (gate grounded) is increased in either 5 V (at GANIL) or 2 V (UCL and RADEF) voltage steps per irradiation run. Each irradiation run is performed at a constant drain voltage up to a total fluence of 3×10^5 ions/cm^2 or until SEB occurs.

The devices were mounted in TO3 packages (see insets in Fig. 2). The standard DUT die have source and gate pads on the sides so that shadowing from bond wires is minimized [10, 11]. However, for several devices, extra bond wires were intentionally added over the die. These extra 20-mil (500 µm) diameter bond wires have no electrically active role because they are connected on both sides on the package drain contact. However, they will induce significant shadowing effects over the die.

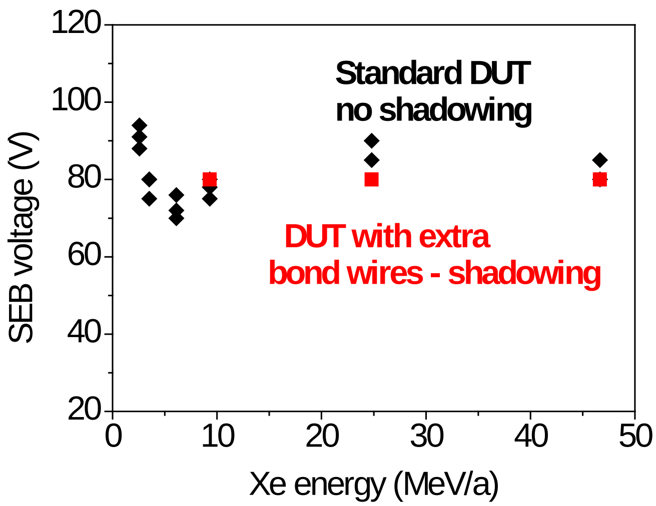

Fig. 2. Destructive Single-Event-Burnout (SEB) voltages for the IR57230SE engineering parts as a function of the Xenon beam energy at GANIL, RADEF and UCL. Both standard devices (without extra bond wires – no shadowing) and devices with extra bond wires were tested. Inset: pictures of the DUTs with or without extra bond wires mounted in TO3.

Fig. 2 compares the SEB voltage for the standard devices and the devices with extra bond wires. For the DUTs with extra bond wires, data were taken only at GANIL, from 9.3 MeV/a up to 47 MeV/a. Data clearly show that the SEB voltage does not vary with the Xenon beam energy. This result was expected because shadowing can result in a large spectrum of particle energies reaching the die [11]. Within this energy spectrum, the worst-case energy particles determine the SEB voltage.

For the standard DUTs without shadowing from extra bond wires, data were obtained at GANIL, RADEF and UCL, from 2.2 MeV/a to 47 MeV/a. Results are consistent between the three facilities. A worst-case energy can be distinguished at about 6 MeV/a, corresponding to the maximum effective LET (69 MeV-cm^2/mg) in the epitaxial layer. At very low energies (2.2 MeV/a), the SEB voltage increases as expected because of the low beam range (26 µm) and the reduced effective LET (39 MeV-cm^2/mg) in the epitaxial layer. However above the worst-case energy, the SEB voltage was expected to increase because of the lower beam LET at higher energy. For example, at 46 MeV/a the effective LET (27 MeV-cm^2/mg) in the 20 µm thick epitaxial layer is reduced by more than a factor of 2 compared to the effective LET at the worst-case energy. However, the SEB voltage only slightly increases from 75 V to 80 V. This effect is called the “specie” effect in [12, 13, 14]. It describes the fact that whatever the energy (except at very low energies), the failure voltage is approximately constant and depends only on the beam specie.

To better understand the mechanisms underlying SEB, charge collection measurements were performed on the 57230SE engineering samples with or without extra bond wires at high Xenon energies (46 MeV/a) at GANIL (Fig. 4). For the devices with extra bond wires, because of shadowing, the charge collection measurements performed at 70 V (below the SEB voltage) clearly show a large collected charge spectrum, reaching the saturation of the charge sensitive pre-amplifier. For the devices without extra bond wires, the collected charge was acquired at different drain voltages (gate grounded). The core of the collected charge distributions slowly increases with drain voltage, but below that required to saturate the preamplifier. However, a few high collected charge events are visible in the distributions, approaching the preamplifier saturation. Such high collected charge events have been measured already with better statistics in [11]. They appear with a relatively low probability, 10^{-3}-10^{-4}, but their maximum deposited charge matches the worst-case energy configuration. Such events might be responsible for premature SEBs, even for devices without shadowing from bond wires. Because SEB measurements are performed at high fluence (> 10^5 ions/cm^2), such low-probability events are present and can trigger SEBs.

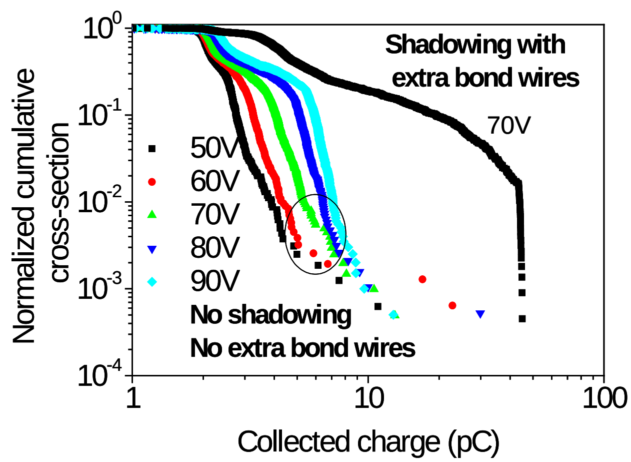

Fig. 4. Collected charge in the IR57230SE engineering devices at GANIL for high energy xenon (46 MeV/a). The devices are either standard (no extra bond wires), or with extra bond wires over the die, inducing shadowing. Each distribution is built from about 2000 transients.

These high collected charge events are likely due to nuclear stopping of the incident ions on target nuclei [15, 16]. In addition to electronic stopping when the ion scatters with the target electrons (usually referred as direct ionization), nuclear stopping also occurs when the incident ion scatters with target nucleus by Coulombic interaction. The incident ion is then significantly slowed down, while the target nucleus may be ejected from its lattice site (resulting in displacement damage). For SEE, when working with a high energy beam, the slowed projectile after nuclear stopping has a higher LET, resulting in higher collected charge events. This analysis will be further developed in the final paper with Geant4 simulations.

C. Charge collection in PIN diode and MM2K

To further understand the effect of beam energy, Fig. 5 displays the experimental characterization of the energy distribution of the Xenon beam at GANIL. These charge collection measurements were performed with the SSBD PIN diode under four conditions of Xe energies at GANIL. For the three lowest energies, the incident ions stop in the depletion region and lose all of their energy in the diode. The measured spectrum then corresponds to the beam energy spectrum as seen by devices under irradiation. The vertical lines correspond to the target energies (3.5-9.3-25 MeV/a) calculated with SRIM. It must be noted that the main peaks of the distributions do not exactly match the target energies. The second point of interest concerns the shape of the distributions: besides the main peak corresponding to direct ionization, a tail of low energy events is visible in all distributions. These events likely come from nuclear stopping of the incident beam before reaching the SSBD diode. Nuclear stopping occurs in the output window, the air, and in some cases the aluminum degrader. When working at relatively high energies, these low energy events, i.e. high LET scattered ions, induce high collected charge events. For example at 25 MeV/a, events as low as about 1000 MeV (i.e. ~ 9 MeV/a Xe) are detected. These low energy events have a high LET (~ 60 MeVcm^2/mg) that could be capable of triggering SEB in a power MOSFET.

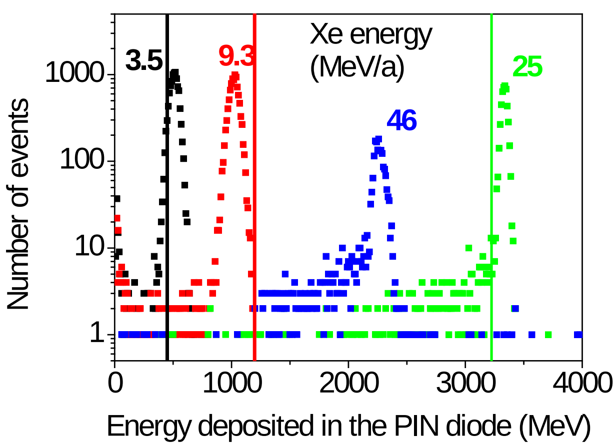

Fig. 5. Charge collected in a planar totally depleted Silicon Surface Barrier Detector (SSBD) at GANIL for different energy conditions (air and Al degrader thicknesses). The distributions are measured with 5×10^3-10^4 incident ions, except for the 46 MeV/a case, obtained with only 2×10^3 ions.

For the highest energy (46 MeV/a), the beam range is longer than the PIN diode depletion region (300 µm). In this case, the distribution displays *both low and high collected charge events on both sides of the main peak.* The low collected charge events are due to nuclear scattering before reaching the SSBD diode and for slowed ions stopping in the SSBD diode, as previously observed in lower energy cases. High collected charge events are due to nuclear scattering at proximity or inside the diode depletion region, *when the scattered ion still has sufficient energy to traverse the diode depletion region, with a higher effective LET than the average LET (main peak).* This high energy case with the SSBD diode is qualitatively similar to charge collection in power MOSFETs where high collected charge events are observed, corresponding to scattered ions, traversing the DUT sensitive layer with a higher effective LET.

IV. Conclusion

Power MOSFETs and SRAMs have been irradiated over a wide range of beam conditions using several different heavy-ion test facilities. Experiments show that the measurement of rare events acquired at high beam fluence, like SEUs below the direct ionization threshold LET in SRAMs, or SEBs in power MOSFETs, are highly sensitive to the beam energy and test conditions. Testing at high fluence will necessarily induce large LET events because of nuclear interactions in the device itself, or before reaching the device in the output window, air and degrader if testing in air. This is typical of high energy testing, and it cannot be avoided.

Note that the probability of rare events due to nuclear interactions does not necessarily increase with the beam energy as observed in the SRAM. There is apparently a worst-case, in the ~10's MeV/a when testing in air. For power MOSFETs, a worst-case was also observed around 6 MeV/a corresponding to the maximum effective LET (i.e. deposited charge) due to direct ionization in the device sensitive volume. However, at higher energies (i.e. lower direct ionization LET) the SEB voltage does not improve, because of nuclear interactions which depend on the beam and target species.

Despite the inevitable nuclear products at high energy, testing at low energy (below the Bragg peak) is not recommended because of even larger variations and uncertainties in effective LET and deposited charge. In any case, the characterization of the beam energy spectrum should be mandatory at all facilities for an adequate analysis of SEE results.

In the final paper, further measurements will be provided, in particular with comparisons of tests in air or vacuum. Geant4 simulations will also be performed to support the analysis. This work has important implications for hardness assurance testing for space environments.

V. Acknowledgment

The authors give special thanks to Jeffrey L. Titus from NAVSEA Crane and Robert A. Reed from Vanderbilt University for encouragements and stimulating discussions.

VI. References

[1] R. Harboe-Sørensen, et al., RADECS 2005 proceedings, Cap d'Agde, Sept. 2005.
[2] R. Harboe-Sørensen et al., *IEEE Trans. Nuc. Sci.*, Vol. 55, No. 6, pp. 3082-3087, Dec. 2008.
[3] R. Harboe-Sørensen, et al., "The Technology Demonstration Module On-Board PROBA-II," to be published in *IEEE Trans. Nuc. Sci.*, Vol. 58, No. 3, June 2011.
[4] S. Liu, et al., to be published in *IEEE Trans. Nuc. Sci.*, Vol. 58, No. 6, Dec. 2011.
[5] K.M. Warren, et al., *IEEE Trans. Nuc. Sci.*, vol. 52, no 6, p. 2125, Dec. 2005.
[6] P. E. Dodd et al. *IEEE Trans. Nuc. Sci.*, Vol. 54, No. 6, pp. 2303-2311, Dec. 2007.
[7] S. Duzellier, et al. *IEEE Trans. Nuc. Sci.*, Vol. 44, No. 6, pp. 1797-1802, Dec. 1997.

[8] S. K. Hoeffgen, et al. to be published at RADECS 2011, Seville, Sept. 2011.

[9] M. P. King, et al. *IEEE Trans. Nuc. Sci.*, Vol. 57, No. 6, pp. 3169-3175, Dec. 2010.

[10] J. L. Titus, et al., presented at the SEE symposium April 1998, and RADECS, Sept. 1998.

[11] V. Ferlet-Cavrois, et al. *IEEE Trans. Nuc. Sci.*, Vol. 57, No. 6, pp. 3515-3527, Dec. 2010.

[12] J. L. Titus, et al., *IEEE Trans. Nuc. Sci.*, Vol. 45, No. 6, pp. 2492-2499, Dec. 1998.

[13] S. Liu, et al. to be published in *IEEE Trans. Nuc. Sci.*, Vol. 58, No. 6, Dec. 2011.

[14] J.-M. Lauenstein, et al. to be published in *IEEE Trans. Nuc. Sci.*, Vol. 58, No. 6, Dec. 2011.

[15] R. A. Reed, et al. *IEEE Trans. Nuc. Sci.*, Vol. 54, No. 6, pp. 3356-3362, Dec. 2007.

[16] R. A. Reed, NSREC Short-course 2008.