Qualification Methodology for Sub-Micron ICs at the Low Noise Underground Laboratory of Rustrel

A. Lesea, K. Castellani-Coulié, G. Waysand, J. Le Mauff, C. Sudre

***Abstract*—Alpha contamination has become a major concern in ICs. To qualify packaging solutions for commercial, industrial, and aerospace/defense components, a program is described. The chosen methodology associates the use of real time testing in altitude and underground environments. Experiments are performed on Xilinx FPGAs. Goals, experiment design, statistical confidence, initial results are analyzed and discussed.**

***Index Terms*— Alpha contamination, FPGA, Low Noise, Real time testing, SER, Underground test.**

I. Introduction

WITH dimensions continuously shrinking, more and more effects due to the very small dimensions involved appear in electronic devices. Among the encountered problems, those created by radioactive impurities and cosmic radiation increase. From the late 1970s, the Soft Error Rate (SER) due to alpha particles had serious consequences for several companies. With decreasing supply voltage and node capacitances, the SER due to alpha particles yet presents a major reliability concern to logic processes because of the decreasing critical charge. Solutions exist to limit alpha contamination but are often costly. For example, packaging alternatives such as a lid coat or flip-chip strongly influence the alpha induced SER. The use of ^{10}B in the process can also greatly influence the SER by enhancing the alpha particle contribution. The alpha induced SER increases more rapidly with decreasing critical charge than neutron induced SER, and for some circuits, the alpha SER becomes comparable to that of neutron SER [1-2]. To remain reliable, the nanoelectronic devices and systems must take into account upsets due to the transitory errors induced by alpha from radioactive contamination, and ideally, be hardened as best as possible. As a consequence, one of the major issues for nanoelectronic companies is today to understand the phenomena related to the radioactive contamination in materials in order to prevent, detect, and analyze them.

In the past, several works have shown the interest of using an underground site to separate the component of the SER caused by cosmic rays from that caused by on-chip radioactive sources of alpha particles [3-5]. This is the chosen methodology presented here for the Rosetta experiment of Xilinx to detect contamination. Indeed, for more than a year, Rosetta has been operating at the Low Noise Underground Laboratory of Rustrel (LSBB) in order to extract any potential alpha contamination contribution to SER from 200 devices under test, in a place devoid of any radiation sources.

In this paper, the choice of the experimental conditions is detailed and explained. The sources of alpha contamination in integrated circuits (ICs) are discussed in order to clearly separate the atmospheric contributions (leading to an indirect source of alphas) from the internal contributions. First results obtained at LSBB on the 130nm Xilinx FPGA are compared with results obtained at ground level and are analyzed.

II. Choice of the Experimental Set-up

A. The atmospheric Rosetta Program

Why the Rosetta program?

The experiment used for this work is based on the Rosetta program. This program [6] was initially used by Xilinx to verify that alpha contamination was not present by comparing upset rates obtained in natural environment at different altitude sites. This program had been created when Xilinx discovered that there was an alpha source which had contaminated a lot of solder bumps in a number of flip-chip packages in 2002. This contamination issue resulted in a financial loss, and a recall of product. It was decided to create a viable test and qualification program to verify that new packaging solutions had solved the contamination issue [7]. Plans began immediately to address prevention of a re-occurrence, as well as a plan for qualification of new substrates.

Manuscript received September 7, 2007.

A. Lesea is with Xilinx, 2100 Logic Drive, San Jose, California, 95124 (Phone: 408 559 7778 – Fax: 408 377 4790, e-mail: Austin.Lesea@xilinx.com).

K. Castellani-Coulié is with L2MP-UMR CNRS 6137 / IMT, Technopôle de Château – Gombert, 13451 Marseille Cedex 20, France (e-mail: karine.castellani@univ-cezanne.fr).

Georges Waysand is with the Low Noise Laboratory of Rustrel Pays d'Apt, La Grande Combe – 84400 Rustrel (e-mail: lsbb@geoazur.unice.fr).

Joel Le Mauff is with Xilinx, Technoparc de l'Aubinière, 2 avenue des Améthystes, BP 13813, 44338 Nantes Cedex 3, France (email: joel.lemauff@xilinx.com).

Christophe Sudre is with INSEET, Route de St Christol, 84400 Rustrel, France (email: csudre@inseet.com)

978-1-4244-1704-9/07/$25.00 ©2007 IEEE

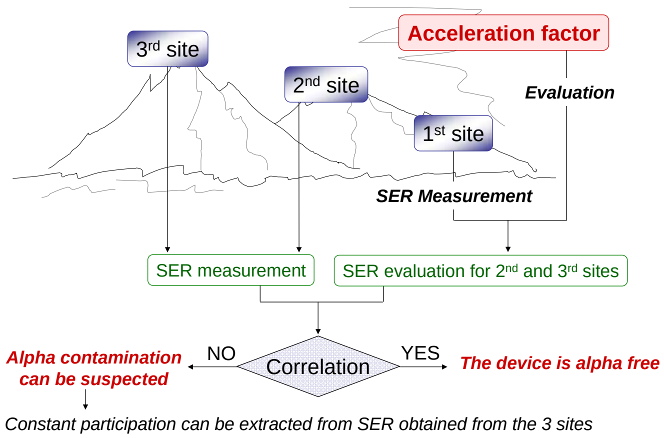

Fig.1: Scheme explaining the first experimental approach used in Rosetta to detect alpha contamination.

First approach

Performing experiment at high altitudes is interesting because it is a natural environment (as opposed to accelerated tests with beams) and because the natural neutron flux, the predominant part of the radiative environment in the atmosphere, increases with altitude. So increasing the altitude of the experiment applies an acceleration factor in measurement, leading to a gain in time measurement. The use of three sites at different altitudes was intended to obtain an evaluation of the tested devices sensitivity submitted to the natural environment and isolate and constant upset rate with time. Once a result is extracted from the first site, the results from the two others sites can be predicted. If a correlation is found between theory and experiment, one can deduce that the device is alpha free. If a difference is found, an alpha contamination can be suspected. In that case, a constant participation in the upset rate obtained from the three sites can be extracted (Fig.1).

This methodology made it possible to verify the low level of alpha particles present in previous 150nm technology packages (estimated at 117 FIT/Mb), and also verify that the newer 130nm packaged product had an alpha upset level of well below the level present in the 150nm product. However, a weak point of that method is that the precision of the results is difficult to evaluate, because the atmospheric upset acceleration rates themselves are not exactly known. These acceleration rates depend on the knowledge of the atmospheric particle flux, and more specifically of the natural neutron flux. This was, and this is still, the object of numerous works and research [8-9]. Moreover, to be sure that any suspicion of alpha contamination is removed, the experiments have to be performed at three different altitudes at least in order to check the correlation between the various obtained results.

Underground approach

Based on previous work, testing devices in an underground environment appeared to be a reliable means to provide a reference for alpha detection [3-5]. So in 2006, Xilinx had established with INSEET[1] a partnership for device underground and altitude qualification. A site with strongly attenuated cosmic rays was found: the Low Noise Underground Laboratory of Rustrel-Pays d'Apt (LSBB) [10]. This site is ideal to extract potential alpha contamination from devices. Indeed, the Rustrel site is 550 meters below the summit of a mountain, and is well suited and characterized for just such experiments. At this depth most (all) of the neutron flux comes from the rock and is much too low in energy to cause an upset in the devices. Thus, the devices under test are insulating from any radiation source. So, only one altitude site is now required in addition with LSBB for a full qualification of devices and systems concerning ground radiation effects. Xilinx devices used in that work have been fabricated not to be sensitive to thermal neutrons and have been tested and proven to be immune to neutrons with energies in the thermal range and below. Thus, as devices are insulated from cosmic rays, alpha contamination will be the most probable cause of upsets (only cause), if upsets do occur.

B. The LSBB site

A key factor, for an underground site, is to keep as low as possible the overall noise to insure the best conditions for the scientific experiments and also to "certify" for scientists and companies the rare-event environment. Indeed, there are an innumerable number of ways that the environment surrounding a digital system can disrupt its operation. The Rustrel site is not the best or deepest in terms of cosmic-rays protection, but, it is definitely good enough due to its location in water-bearing calcite rock, and an excellent underground laboratory in terms of lowest noise from sources of any kind.

The LSBB is located in the southern "Plateau d'Albion", France, under the "Grande Montagne" massif. It was the launch control center #1 for the French strategic nuclear defence. This installation was designed and built in order to remain operational even in the case of a nearby nuclear blast. As a result, it is resistant to radioactive clouds, thermal impacts, mechanical waves and electromagnetic pulses. Since the decommissioning of the underground launch control room of the ground based component of the French nuclear missile system in 1997, the whole installation has been turned into a cross-disciplinary underground low-noise laboratory. The LSBB[2] is a unique low-noise underground laboratory because of its initial military conception and its location far from large cities, industrial and heavy traffic and within a karstic rock system. The whole tunnel is 3.5 km long with horizontal access and an average slope of 2%, the deepest point being 550m below the surface. The characteristics of this site make it especially suited for rare-event searches. Deriving benefits from LSBB location and it is technical characteristics, coupled experiments concerning dark matter physics, hydrogeology, thermo-hydromechanics, electro-seismic imaging, seismology and seismo-magnetism are conducted within LSBB by

[1] INSEET, http://www.inseet.com, info@inseet.com
[2] http://lsbb.unice.fr

different research teams. The LSBB is in full agreement with technical and human requirements prescribed by the JESD89A norm for real-time testing site (access and operating conditions, test system configuration, sensor environment)[3].

The tests zones are at below ~1500 m.w.e. (Meter Water Are equivalent), i.e. -550m in calcite rock. This depth is more than sufficient for the shielding of the secondary cosmic neutrons as shown in Fig. 2.

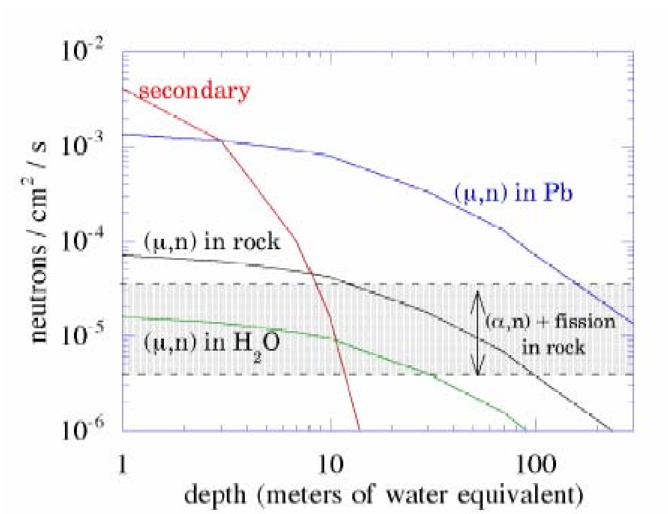

Fig.2: Components of neutron flux as a function of underground depth [11]. The contribution to the flux from muon interactions is derived from the systematics and measurements of G.V. Gorshov et al., Sov. J. Nucl. Phys. 13 (1971).

Beyond a few hundreds of m.w.e in fact the thermal neutrons resulting from the surrounding rock are most numerous independently of the nature of the shielding of the experiments. An increased depth does not bring a reduction of flux of low energy neutrons. Fig.2 shows the variation of each component of the flux of neutrons according to the depth below of a few tens of meters. The colored band is that of the characteristic contributions due to the natural radioactivity of the rocks based on deep measurements and concentrations of U and Th in the Earth's crust. Muons flux below -550m is ~ 0.5* 10-3μ/m2/s . -550 is not considerable compared to other existing underground facilities. But, beyond a hundred meters of shielding, the radioactivity of the rock is dominant compared to the cosmic radiation, the neutrons resulting from reaction (μ, N) are in minority compared to those resulting from the rock. The flux of muons is thus a secondary phenomenon of importance for the activities of the LSBB. For current and near future devices, the contribution of neutrons from the rock is low enough to be neglected. However, the characterisation of these neutrons is useful for a full qualification of the LSBB site for device tests. Note that any soft error event can be cross-correlated to seismic event (natural or entropic), ionosphere magnetic storm, or electromagnetic event. Fig.3 shows how Rosetta is installed in Rustrel. An internet line allows live communication with Xilinx in San Jose.

III. Alpha contamination in Silicon ICs

The atmospheric radiation environment results mainly from the interaction of charged primary particles, from cosmic rays, with the atmosphere. The particles thus created undergo new reactions with the air molecules, inducing a prevalence of the neutrons from airplane altitudes down to ground level. The neutrons act indirectly by creating secondary ionizing particles when interacting with the material. According to the energy of the incident particle, the range of secondary particles can go from less than one micron to several tens, even hundreds, of microns for the lightest particles, such as alpha. It is considered that neutrons are the only primary particles to take into account in the atmosphere [12-13]. Charged particles can be easily stopped by shielding but not neutrons which can interact after having crossed several meters of material. This problem is the most dominant as these particles are most abundant of the atmospheric radiation environment.

A first significant source of ionizing particles in electronic devices can come from the interaction of low-energy cosmic ray neutrons with boron. It can be considered as an indirect source of alphas because it interacts with a neutron. Boron is used as a p-type dopant and implant species in silicon and is also used in the BPSG[4] dielectric layers formation. Boron is composed of two isotopes, ^{11}B (80.1%) and ^{10}B (19.9%). The

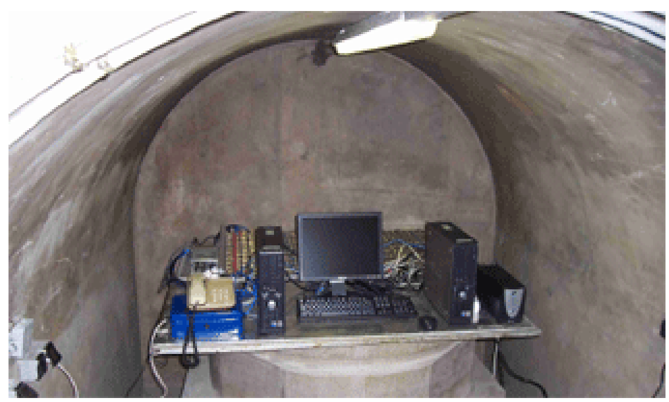

Fig.3: Rosetta at -550m, in LSBB.

^{10}B is unstable when exposed to neutrons and breaks into ionizing fragments shortly after absorbing a neutron. Then alpha particles are created. With a thermal neutron capture cross-section of about 4000 barns[5] for ^{10}B (extremely high compared to most other isotopes in the semiconductor materials), this interaction is a particular concern for alpha emission. Works [14-15] by R. Baumann have shown for conventional BPSG-based semiconductor processes, the BPSG is the dominant source of boron reactions and in some

[3] The LSBB scientific committee has commissioned INSEET to welcome scientists and companies to develop scientific activity at LSBB.

[4] BoroPhosphoSilicate Glass

[5] 1barn=10^{-24} cm² per nucleus

cases can be the primary cause of soft errors. **Xilinx does not use ^{10}B in any of its fabrication processes**.

In parallel, telluric radiation, due to the presence of transmitting impurities of alphas in materials can also be an error source for nanoelectronic components. This kind of direct contamination was detected initially by INTEL in 1978 [16] then by IBM in 1987 [17] after having noted error rates which can be nearly 20 times higher than the normal error rates on some their production lines. First SEU problems were detected in materials used for IC packaging. These materials were found to contain radioactive atoms traces which emit alpha particles [18-19]. The alpha particle is composed of two neutrons and two protons. It is a doubly charged Helium cores, emitted by heavy during radioactive decay [20]. Several materials have been identified as being source of alpha particles (Pb, U, Th …) and can be found both in ICs or in the nearby packaging environment. A primary alpha emitter is lead (Pb) used in ICs solder. ^{210}Pb, a lead isotope, is radioactive and can decay through β emission to ^{210}Po, which itself is radioactive and emits alpha particles. Some manufacture processes, where the ^{210}Po use is required can also be responsible for the alpha emitter increase. Today, the ^{210}Po is considered to be the most likely source of alpha emission in ICs. The trend is to remove lead in solders (63%Sn / 37%Pb). But lead free solders are not an ideal solution considering that ^{210}Pb appears too as contaminant in Ag, Bi and Sb. Alphas also come from other emitters such as uranium and thorium in ceramic packages. Solutions exist to limit alpha contamination but they are often costly, and usually used in applications where reliability is mandatory. However, the effort to purify material used in the ICs manufacture has contributed to a substantial reduction of the in situ alpha particles emission. Even if this reduction is satisfactory for microelectronic devices, it will not be enough for devices whose size will not exceed tens of nanometers. The consequences could be dramatic and it is now mandatory to evaluate the sensitivity of circuits to this contamination.

IV. The Rosetta experiment at LSBB

The goal of such an experiment is to discover if there is any alpha particle contamination as quickly as possible to be able to correct the problem. The size of the array of devices under test is the only variable that can be controlled, as time being the other variable can not be accelerated in any way for this test. Each Rosetta experiment consists of multiple sets of 100 of Xilinx FPGAs of differing technologies and is located at seven different altitudes. For this experiment, we consider the use of two arrays: one located in the atmosphere, and one underground; and analyze the results. Based on the result, it is proposed that a future series of tests to be conducted as part of a standard qualification flow.

A. Design of Experiment

The device studied in this work is the 130nm xc2vp50 FGPA. The number of components under test was decided to be 200 units, or two separate arrays of 100 components each. Because there are so different, configuration memory and Block RAM (BRAM) memory are studied separately. The two arrays comprise 13.4512 Megabits per device configuration and 4.276 Megabits per device BRAM so 2,692 Mbits of configuration and 855 Mbits of BRAM under test.

B. Statistical Confidence

With this many bits under test, to verify to a 95% confidence level that the alpha upset rate is less the total upset rate at sea level, the authors conclude that we need to have at least 4,400 hours, or roughly 6 months of data. Note that the 95% confidence level assumes a worst case of 3.7 events, event if none are measured. Thus, if we do not use the multiplier of 3.7, we have a first order readout in 3.7 times less time, or roughly forty days. Given that there are no upsets in the first 40 days, we can begin to feel more confident that alpha contamination is not present. This may seem too soon to draw any conclusions, but alpha contamination sources typically create so many upsets, that if present, the signature is often very easy to observe. For example, in the previous case [3], the upset rate was roughly once every 71 days, per device. So, for 200 devices, that would be about 2.5 upsets per day, for 100 upsets in 40 days. Having had 0 upsets in the same time period is then an excellent indicator that the proper materials were used to construct and assemble the components.

Already referred to above, the Rosetta program states its results at the 95% confidence interval. So, for example, if a year long experiment has had 100 upsets, we state that the 95% limits to this are 81.4 to 121.6 events. Such limits are found by referring to table lookups for confidence limits for a Poisson process (like radioactive decay, and the occurrence of neutron upsets from cosmic rays). Given that Rustrel is likely to yield 0 events, even after two or three years, we must establish a lower bound, below which we are just not concerned with the presence of alpha particles. Some have set this threshold at one half the sea level upset rate. Others have set this rate even higher, so as to save costs and not require ultra low alpha packaging materials. For Xilinx devices, these limits have not been formalized, but a level well below one half is the stated goal.

C. Results from LSBB for 130nm FPGAs

The 200 components have been running at LSBB for 7,100 hours. **1 error has been detected**.

All the metrology abilities of the LSBB, ie simultaneous seismic and magnetic measurements done, among others, by SQUID (Superconducting Quantum Interferometric Device) magnetometer [21] at the exact time of the detected upset, confirmed the fact that this error is internal. The very low noise environment and the very high sensitivity of the SQUID make it possible to perform very sensitive measurements of the earth magnetic field from 0 to 40Hz from Femto-Tesla. Then, various group of phenomena, like magneto-ionospheric or magneto-seismic events, can be discriminate.

From an electrical point of view, the low noise environment of LSBB ensures very accurate measurements, insulated from parasitic noise. Preliminary works performed at LSBB showed the influence of the electromagnetic environment on Si and SiC diodes [22]. The obtained results pointed out that the electrical characteristics can be 1.5 times better at LSBB than in usual conditions. Other experiments are being conducted in that field.

From these considerations, several explanations can be proposed to explain the observed single event:

1) Bad bit in the part. If so, the same bit should upset again. This same bit flip has not re-occurred, so this hypothesis is probably not valid.
2) Signal integrity (noise): power supply, cross talk, read-disturb.
3) Alpha associated with a solder bump.

If the third hypothesis is considered, this means a 95% worst case lower bound of 52.3 FIT/Mb for the configuration and 164 FIT/Mb for the BRAM (Fig. 4). Note that in the contaminated lots from 2002, the rate was approximately 30,000 FIT/Mb which is very far from this result. This single event is in agreement with predictions. Indeed, the expected number for one year of experiment was 4. Only having 1 event means that the residual alpha in the package is at least 4 times better than it was calculated from predictions from the level of contaminants supposed to be found in epoxy under-fill, and ultra low alpha solder bumps. This result itself is important. But more important is the detection of events during the same time, for the same device tested in the atmosphere. For example, at ground level (123m, acceleration factor 1.08), for 200 components and 7,750 hours of test 11 configuration errors have been detected, along with 2 BRAM errors (Fig. 4). The resulting FIT rate predictions are 489 FIT/Mb for configuration, and 280 FIT/Mb for BRAM. That is the reason why another location is of high interest in addition to the LSBB.

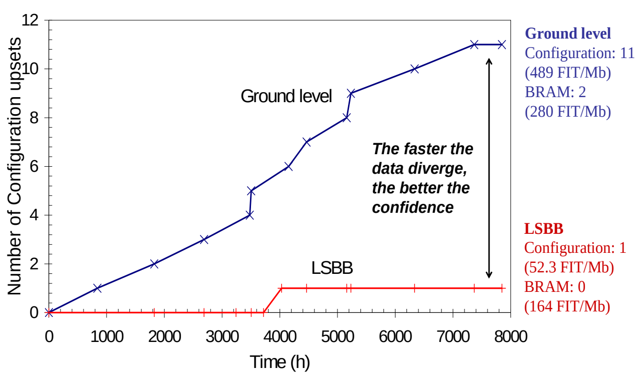

Fig.4: Number of events vs. Time exposure.

D. Discussion

One important question is: "When do I know I do not have an alpha contamination issue?" Alpha particles undergo radioactive decay, and their decay statistics are best predicted by using a Poisson distribution. For a 95% confidence interval (5% chance to be wrong, 95% to be right), you would like to know how many devices, and how long, you must wait. By using the LSBB all of it own, no other experiment anywhere, it is just a matter of time, and parts. Assuming you get 0 upsets, Poisson says you may actually have had 3.7 events to be 95% confident. Thus, suppose the FIT rate desired for alphas is 100 FIT/Mb. You must wait until the number of bits time implies that even with 0 upsets, the FIT rate is less than 100 FIT/Mb (you assume that you have 3.7 upsets, and wait until the result drops to 100). If you have another set of parts, at an atmospheric location, after some amount of time, you will probably have a non-zero number of errors. Then you can predict a FIT rate and a confidence interval based on the number of events. That is what the Rosetta is now able to provide thanks to measurements in various altitude locations and the use of the LSBB. With a low noise underground laboratory, like LSBB, associated to another atmospheric location, you obtain two sets of data: **then the faster the data diverges, the better the confidence** (no events underground, some events above ground). Thus the LSBB becomes one required element of two major elements in a reliability testing plan for natural environment.

Note that the BRAM results after 7100 hours are still close in both cases (LSBB and ground level). The "small" number of tested bits, compared with the number of tested bits for configuration (855 Mbits instead of 2,692 Mbits) can explain the reduced number of errors observed for BRAM. However, the trend is the same than for configuration: the number of errors is much higher at ground level than at LSBB.

V. CONCLUSIONS

The authors have collaborated to develop a process to qualify how the substrate packages are verified so as not to have any sources of alpha particle contamination. It appears that the association of the Rosetta experiment and the LSBB provides an ideal testing plan to get a complete evaluation of the devices sensitivity in natural environment. By testing the components in LSBB and in its unique environment, it is possible to check easily if the components are contaminated or not: no need to cross-correlate events due to contamination of the packaging, and those due to the natural atmospheric environment. This is a considerable gain of time and precision for the detection of alpha contamination.

VI. REFERENCES

[1] J.F. Ziegler, H. Puchner, "SER – History, Trends and Challenges: A Guide for Designing with Memory ICs", pp. 3-18, 2004.

[2] L.W. Massengill, "Cosmic and Terrestrial Single-Event Radiation Effects in dynamic Random Access Memories", in IEEE Trans. On Nucl. Sc., vol.43, no.2, pp. 576-593, April 1996.

[3] H. Kobayashi et al., "Soft errors in SRAM devices induced by high energy neutrons, thermal neutrons and alpha particles", in: Electron Devices Meeting, 2002. IEDM '02. Digest. International, 2002.

[4] T. J. O'Gorman, "The Effect of Cosmic Rays on the Soft Error Rate of DRAM at Ground Level", IBM J. Res. Develop., vol.40, no.1, pp.41-50, April 1994.

[5] T. J. O'Gorman et al., "Field testing for cosmic ray soft errors in semiconductor memories", IEEE Trans. On Nucl. Sc., vol.41, no.4, pp.553-556, January 1996.

[6] Austin Lesea, Saar Drimer, Joseph Fabula, Carl Carmichael and Peter Alfke, *The Rosetta Experiment: Atmospheric Soft Error Rate Testing in Differing Technology FPGAs.* IEEE Transactions on Device and Materials Reliability, Vol. 5, Number 3, September 2005.

[7] Xilinx, *Customer Advisory: Flip-Chip Package Substrate Solder Issue,* January 19, 2004.
http://tinyurl.com/fynf9

[8] B. Wiegler, A.V. Alevra, "NEMUS – the PTB Neutron Multisphere Spectrometer: Bonner spheres and more", in Nuclear Instruments and Methods in Physics Research, pp.36-41, 2002.

[9] M.S. Gordon, P. Goldhagen, K.P. Rodbell, T.H. Zabel, H.H.K. Tang, J.M. Clem, and P. Bailey, "Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground", in IEEE Trans. On Nucl. Sc., vol.51, no.6, pp.3427-3434, December 2004.

[10] Laboratoire Souterrain à Bas Bruit de Rustrel – Pays d'Apt, Université de Nice Sofia- Antipolis, http://lsbb.unice.fr/

[11] G. Waysand, D. Bloyet, J.P. Bongiraud, J.I. Collar, C. Dolabdjian, Ph. Le Thiec, "First Characterization of the Ultra-Shielded Chamber in the Low-noise Underground Laboratory (LSBB) of Rustrel Pays d'Apt", Nucl. .Instrum. Meth. A444 (2000) 336-339, Oct 1999.

[12] E. Normand, "Single Event Upset at Ground Level", in IEEE Trans. On Nucl. Sc., vol.43, no.6, pp.2742-2750, December 1996.

[13] R.H. Edwards, "Technical Specification for Atmospheric Radiation Single Event Effects, (SEE) on Avionics Electronics", in IEE Seminar on Cosmic Radiation 6th, December 2005.

[14] R.C. Baumann et al., "Boron Compounds as a Dominant Source of Alpha Particles in Semiconductor Devices", in Proc. 33rd Int'l Reliability Physics Symp. (IRPS), IEEE EDS, pp. 297-302, 1995.

[15] R.C. Baumann et al., "Neutron-Induced ^{10}B Fission as a major source of soft errors in high density SRAMs", in Elsevier Microelectronics Reliability, vol.41, no.2, pp. 211-218, 2001.

[16] http://www.ida.liu.se/~abdmo/SNDFT/docs/ram-soft.html

[17] http://www.research.ibm.com/journal/rd/401/curtis.html

[18] C. Cabral et al., "Alpha particle strategies to reduce chip soft error upsets", *Journal of Applied Physics, 2007*.

[19] Brett M. Clark et al., "Alpha radiation sources in low alpha materials and implications for low alpha materials refinement", Thin Solid Films, 2004.

[20] H.S. Al-Medainy, N.A. Al-Mohawes, H.P. Chou, "Determination of Uranium and Thorium Concentrations in Integrated Circuit Packaging Materials", J. Radioanal. Nucl. Chem., Letters, pp. 341-350, 1989.

[21] Maurice Pyée, Rachid Talhi, Malay Ranjan Tripathy, "SQUID ANTENNA PATTERN in the Low-noise Underground Laboratory (LSBB) of Rustrel Pays d'Apt", URSI, August 2002.

[22] L. Ottaviani et al., "Influence of electromagnetic environment on Si and SiC diodes electrical characteristics", 9th Technical and Scientific Meeting of ARCSIS, STUniversity, Fuveau (France), 16-17 Novembre 2006..