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Terrestrial Radiation Effects in ULSI Devices and Electronic Systems

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TERRESTRIAL RADIATION EFFECTS IN ULSI DEVICES AND ELECTRONIC SYSTEMS

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To my daughters, Akane and Hikari

About the Author

Dr. Eishi Hidefumi IBE received his BS degree in Physics from Kyoto University, Japan in 1975, and his PhD degree in Nuclear Engineering from Osaka University, Japan in 1985.

He has joined the Atomic Energy Research Laboratory, Hitachi Ltd in 1975. He was promoted to chief researcher in the Yokohama Research Laboratory (formerly Production Engineering Research Laboratory), Hitachi Ltd. in 2006.

He has made outstanding accomplishments in nuclear engineering during the first 20 years of his career, in particular radiation effects on water (radiolysis) and component materials, and in single event effects on semiconductor devices during the last 18 years. His expertise covers very wide areas of sciences, such as elementary particle/cosmic ray physics, nuclear/neutron physics, semiconductor physics, mathematics and computing technologies, ion-implantation/mixing and accelerator technologies, electro-chemistry, database handling, RBS (Rutherford Backscattering Spectrometry)/Auger/SEM (Scanning Electron Microscopy)/Laser-beam micro analysis, and so on.

He has carried out pioneering work on simulation techniques of water radiolysis in the coolant of nuclear power plants to reveal that water coolant in the core decomposes into H_2 and H_2O_2 . He has also established a theoretical basis for the hydrogen water chemistry techniques used to suppress oxidising H_2O_2 , which is now widely applied to Japanese boiling water reactors to mitigate inter-granular stress corrosion cracking of the component materials. He has received awards from the

Japanese Atomic Energy Society in 1986 and 1990, and from the American Nuclear Society in 1996.

During the last 18 years, he has dedicated himself to the development of quantification and mitigation techniques for terrestrial neutron-induced soft error in electronic devices and components. He developed the novel soft-error models for CMOS (Complementary Metal Oxide Semiconductor) devices. The models have been utilised to design more reliable semiconductor memory devices and logic gates, bringing in the breakthrough knowledge on the nature of terrestrial neutron soft error. Under his leadership, novel experimental techniques to quantify soft-error susceptibility of the devices and components have been developed and accepted as international standards.

He has contributed to IEEE journals such as *EDS* and *TNS*, conferences such as IRPS, IOLTS, ICICDT, WDSN, NSREC, RADECS, RASEDA, ICITA and SELSE as a program committee member, or a reviewer in the field of neutron-induced faults/errors/failures. He has authored more than 90 international technical papers and presentations including 25 invited contributions in the field of radiation effects. He has reviewed more than 200 technical papers responding to requests from the Chairs of the journals and conferences. This accumulation has given him wide and deep scope in the field of single event effects.

Dr. Ibe was promoted to IEEE Fellow for contributions to analysis of soft errors in memory devices in 2008. Some of his achievements are now accessible worldwide through his recent publications with World Scientific Inc. (2008) and Springer (2010, 2011).

Preface

In everyday life, we do not recognise the presence of terrestrial radiation – secondary particles are produced from cosmic ray and radiation from radioisotopes at ground level. Terrestrial radiation is so weak (low flux) that they do not have any visible or recognisable influence on human tissues, but it does have an impact on LSI (Large Scale Integration), VLSI (Very large scale integration) and ULSI (Ultra large scale integration) devices in electronic systems at ground level.

When I was a fourth grade student of the Kyoto University in 1974, my major subject matter was the measurement of lifetime of terrestrial muon. At that time, no one, including me, knew about or even imagined such impacts from terrestrial neutrons.

Rapid progress in semiconductor industries has forced us to be aware of the impacts of terrestrial radiation on semiconductor devices. First, alpha-ray soft error from contaminated radioisotopes on/in the DRAM (Direct Random Access Memory) and SRAM (Static Random Access Memory) devices. As the readers will see in this book, terrestrial neutron-induced soft error has been unacknowledged up until the late 1990s for many reasons. As device scaling has nosedived into below 100 nm, the impacts of terrestrial radiation has spread very widely and deeply. Not only terrestrial neutrons but also other terrestrial radiative particles such as protons and muons are recently among the focus of scientific investigations. Beyond memories, sequential and combinational logic devices and circuits are also being scrutinised. Concerns over failures have broadened from servers/routers to the automobile industry.

It is commonly recognised now that failures in electronic systems due to faults or errors introduced in devices/circuits by terrestrial radiation can only be mitigated by the combination or cooperation of mitigation techniques in two or more stack layers such as substrate, cell, circuit, CPU (Central Processing Unit), middleware, OS (Operating System) and application. This is a very challenging task that requires a wide variety of scientific fields like astronomy, cosmic ray physics, nuclear physics, accelerator physics, semiconductor physics, circuit theory, computer theory, numerical simulation, EDA (Electric Design Automation) tools, coding theory, reliability physics, database handling, and so on.

Meanwhile, this task is fascinating. During my research in this field, I have learned a number of exciting facts about the Earth.

We cannot live without air that is only a 50 km thick layer above the Earth - $1/250$ of the diameter of the Earth. An astronaut has a limit to how long he can stay in the inner/outer space due to the limit of radiation exposure by cosmic rays. We, humankind, cannot live on a planet without air and have been protected from harsh cosmic radiation in outer space by only this very thin layer of air in the Earth.

Beautiful aurora australis and borealis are the outcome of interactions between cosmic rays and the atmosphere.

Carbon-14 that is used for radiocarbon dating is produced by nuclear reaction of nitrogen-14 and cosmic ray proton in the atmosphere. Even clouds in the sky have recently been revealed to be mostly triggered by cosmic rays according to CERN's team report.

The author hopes that this book will trigger the readers' interest in the impact of cosmic rays on the Earth and our

everyday lives.

16 April 2014

Eishi H. Ibe

Enjoying scuba diving in Saipan, USA

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Acronyms

| | |
|-------|--|
| ACE | Architectural Correct Execution |
| ALLS | Aligned Laboratory System |
| ALPEN | ALpha Particle source/drain PENtration |
| ALS | Absolute Laboratory System |
| ALU | Arithmetic-Logic Unit |
| AMUSE | Autonomous MUltilevel emulation system for Soft Error evaluation |
| ANITA | Atmospheric-like Neutrons from thIck TArget |
| AOI | Area Of Interest |
| ASIC | Application Specific Integrated Circuit |
| ASIL | Automotive Safety Integrity Level |
| ASTEP | Altitude Single event effects Test European Platform |
| AVF | Architectural Vulnerability Factor |
| AVP | Architectural Verification Program |
| BAN | Body Area Network |
| BCDMR | Bistable Cross-coupled Dual Modular Redundancy |
| BICS | Built-In Current Sensor |
| BISER | Built-In Soft Error Resilience |
| BIPS | Built-in Pulse Sensor |
| BIST | Built-In Self Test |
| BL | Bit Line |
| BNL | Brookhaven National Laboratory |
| BOX | Buried Oxide |
| BPSG | Boron Phosphor Silicate Glass |
| BUT | Board Under Test |
| CAM | Content Addressable Memory |
| CAN | Controller Area Network |

| | |
|------------------|--|
| CCD | Charge Coupled Device |
| CHB | CHecker Board |
| CHBc | CHecker Board complement |
| CL | Confidence Level |
| CLR | Cross-Layer Reliability |
| CM | Center of Mass |
| CMOS | Complementary Metal Oxide Semiconductor |
| CMP | Chemical Mechanical Polishing |
| CNL | UC Davis Crocker Nuclear Laboratory |
| CNRF | Cold Neutron Research Facility |
| CORIMS | COsmic Radiation IMPact Simulator |
| CPU | Central Processing Unit |
| CRAM | Configuration Random Access Memory |
| CRC | Cyclic Redundancy Code |
| CYCLON | Cyclotron of Louvain la Neuve |
| CYRIC | CYclotron and RadioIsotope Center |
| DCC | Duplication + Comparison + Checkpointing |
| DF | Derating Factor |
| DICE | Dual Interlocked storage CELL |
| DLL | Delay Locked Loop |
| DMR ₁ | Dual Modular Redundancy |
| DMR ₂ | Dynamic Memory Reconfiguration |
| DOA | Design On Average |
| DOAV | Design On Average and Variation |
| DOUB | Design On Upper Bound |
| DPM | Defects Per Million |
| DRAM | Dynamic Random Access Memory |
| DSP | Digital Signal Processor |

| | |
|--------|---|
| DUE | Detected Unrecoverable Error |
| DUT | Device Under Test |
| ECC | Error Correction Code/Error Checking and Correction |
| EDA | Electric Design Automation |
| EDAC | Error Detection And Correction |
| EMI | Electro-Magnetic Interference |
| EX | Execution |
| FBE | Floating Body Effect |
| FDSOI | Fully Depleted SOI |
| FF | Flip-Flop |
| FFDA | Field Failure Data Analysis |
| FIT | Failure In Time |
| FPGA | Field Programmable Gate Array |
| FRAM | Ferroelectric Random Access Memory |
| GDS | Graphic Data System |
| GEM | Generalized Evaporation Model |
| GPS | Global Positioning System |
| GPU | Graphic Processing Unit |
| GPGPU | General Purpose GPU |
| GPU | Graphic Processing Unit |
| GTO | Gate Turn-Off Thyristor |
| HA | High Altitude |
| HHC | Hierarchical Hardware Checkpointing |
| HHFL | Heavy Halt Failure |
| ICICDT | International Conference on IC Design and Technology |
| ICITA | International Conference on Information Technology and Applications |

| | |
|--------|---|
| ID | Instruction Decode |
| IF | Instruction Fetch |
| IGBT | Insulated Gate Bipolar Transistor |
| IOLTS | International On-Line Testing Symposium |
| INC | Intra-Nuclear Cascade |
| IRPS | International Reliability Physics Symposium |
| IUCF | Indiana University Cyclotron Facility |
| JAXA | Japan Aerospace Exploration Agency |
| JESD | JEDEC Standard |
| J-PARC | Japan Proton Accelerator Research Complex |
| LABIR | inter Layer Built-In Reliability |
| LAMPF | Los Alamos Meson Physics Facility |
| LANSCE | Los Alamos National Science Center |
| LBNL | Lawrence Berkeley National Laboratory |
| LEAP | Layout design through Error Aware Placement |
| LENS | Low-Energy Neutron Source |
| LET | Linear Energy Transfer |
| LFSR | Linear Feedback Shift Register |
| LHFL | Light Halt Failure |
| LIN | Local Interconnect Network |
| LINAC | Linear particle Accelerator |
| LNL | Laboratori Nazionali di Legnaro |
| LSI | Large Scale Integration |
| LTFL | Latency Failure |
| LUT | Lookup Table |
| MA | Memory Access |
| MBU | Multi-Bit Upset |
| MCBI | Multi-Coupled Bipolar Interaction |
| | Multi-Cell Upset |

| | |
|------------------|---|
| MCU ¹ | |
| MCU ² | Micro Control Unit |
| MF | Masking Factor |
| MFTF | Mean Fluence To Failure |
| MNFL | Marginal Failure |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| MPR | Memory Page Retire |
| MTTF | Mean Time To Failure |
| MTTR | Mean Time To Repair |
| NBTI | Negative Bias Temperature Instability |
| NCAP | European New Car Assessment Programme |
| NIST | National Institute of Standards and Technology |
| NMIJ | National Metrology Institute Japan |
| NoC | Network on Chip |
| NSAA | Nonstop Advanced Architecture |
| NSREC | Nuclear and Space Radiation Effects Conference |
| NYC | New York City |
| OS | Operating System |
| PC ¹ | Program Counter |
| PC ² | Power Cycle |
| PC ³ | Personal Computer |
| PCB | Printed Circuit Board |
| PCSE | Power Cycle Soft-Error |
| PDSOI | Partially Depleted SOI |
| PHITS | Particle and Heavy Ion Transport Code System |
| PIPB | Propagation Induced Pulse Broadening |
| PLL | Phase Locked Loop |

| | |
|--------|--|
| PVF | Program Vulnerability Factor |
| QMN | Quasi-Monoenergetic Neutron |
| RADECS | RADIation Effects on Components and Systems |
| RAM | Radom Access Memory |
| RAP | Resilience Articulation Point |
| RAS | Reliability, Availability and Serviceability |
| RASEDA | RADIation effects on SEMiconductor Devices for space Application |
| RCNP | Research Center for Nuclear Physics |
| RHBD | RADIation Hardened-By-Design |
| RIIF | Reliability Information Interchange Format |
| RILC | RADIation Induced Leakage Current |
| RMA | Return Material Authorisation |
| ROM | Read Only Memory |
| RTL | Register Transfer Level |
| RTOS | Real Time Operating System |
| SAW | Surface Acoustic Wave |
| SBRM | Symptom Based Redundant Multithreading |
| SBST | Software-Based Self-Test |
| SBU | Single Bit Upset |
| SDC | Silent Data Corruption |
| SEALER | Single Event Adverse and Local Effects Reliever |
| SEB | Single Event Burnout |
| SECDED | Single Error Correction and Double Error Detection |
| SEE | Single Event Effect |
| SEFI | Single Event Functional Interrupt |
| SEFR | Single Event Fault Rate |
| SEGR | Single Event Gate Rupture |

| | |
|-------|--|
| SEILA | Soft Error Immune LAtch |
| SEL | Single Event Latchup |
| SELSE | Silicon Errors in Logic—System Effects |
| SEM | Soft Error Mitigation |
| SER | Soft-Error Rate |
| SES | Single Event Snapback |
| SESB | Single Event SnapBack |
| SET | Single Event Transient |
| SEU | Single Event Upset |
| SEUT | Single Event Upset Tolerant |
| SHE | Software Hardening Environment |
| SIL | Safety Integrity Level |
| SILC | Stress Induced Leak Current |
| SIMS | Secondary Ion Mass Spectrometry |
| SITR | Self-Imposed Temporal Redundancy |
| SLC | Single Level Cell |
| SLFL | Silent Failure |
| SOI | Silicon On Insulator |
| SPFD | Sets of Pairs of Functions to be Distinguished |
| SPICE | SimulationProgram with Integrated Circuit Emphasis |
| SRAM | Static Random Access Memory |
| SRIM | Stopping and Range of Ions in Matter |
| STEM | Soft and Timing Error Mitigation |
| STI | Shallow Trench Isolation |
| TAMU | Texas A&M University |
| TID | Total Ionizing Dose effect |
| TCAD | Technology Computer-Aided Design |
| TID | Total Ionisation Dose |