Total dose radiation test methodologies for advanced spacecraft electronics experiencing Enhanced Low Dose Rate Sensitivity

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Abstract

The purpose of this thesis is to determine whether hydrogen can be implanted into electronic components for the goal of investigating low ionising dose rate sensitivity, and using this to suggest whether hydrogen implantation can be used as an accelerated method to detect ELDRS (Enhanced Low Dose Rate Sensitivity) susceptibility.

Current ground testing methods for total ionising dose irradiate using cobalt-60 at dose rates greater than 10mGy(Si)/s up to 200Gy. It has been found that bipolar devices show an increased susceptibility to radiation induced damage at dose rates below 10mGy(Si)/s known as ELDRS. Current research has linked ELDRS susceptibility with hydrogen content within the integrated circuit and experiments based upon hydrogen soaking de-lidded bipolar devices demonstrate this relationship, however this has not led to an accepted method for testing ELDRS susceptibility in previously un-tested devices.

In this thesis, a novel proposal is put forward whereby bipolar devices are directly implanted with hydrogen using a targeted ion beam in order to accelerate the testing process.

Hydrogen implantation via a 600keV ion beam has been achieved to a level of $10^{17} \text{H/cm}^2$ in Analog Device’s AD590KF temperature transducer, and $10^{14-15} \text{H/cm}^2$ in National Semiconductor’s LM124 quad operational amplifiers. Devices were decapped, optically analysed, and targeted with a focussed proton beam. These devices were then irradiated at 15μGy/s, 5mGy/s and 15mGy/s. Increased degradation was seen at lower dose rates which was matched by high dose rate irradiation of the implanted devices followed by a room temperature anneal. The use of ion implantation for the development of an accelerated ELDRS test method is proposed.

This thesis demonstrated that hydrogen can be succesfully implanted into devices, established an upper bound for the LM124 for implantation and a lower bound for hydrogen remaining in the target area and the effect of hydrogen implantation on the AD590 temperature transducer is discussed. This thesis concludes by suggesting hydrogen implantation as a method for use by manufacturers during the design and investigation of intrinsically ELDRS-free technologies.
# Contents

1 Introduction
   1.1 Motivation ........................................... 14
   1.2 Objectives ........................................... 15
   1.3 Novelty .............................................. 15
   1.4 Introduction to ionising radiation ................. 17
      1.4.1 Charged radiation. ............................ 18
      1.4.2 Uncharged radiation. ......................... 19
   1.5 The effects of ionising radiation on matter ....... 20
      1.5.1 Pair production. .............................. 20
      1.5.2 The photoelectric effect. .................... 20
      1.5.3 Compton scattering. .......................... 21
      1.5.4 Ballistic interaction ......................... 22
   1.6 Semiconductors .................................. 23
      1.6.1 The PN junction ............................... 24
      1.6.2 Bipolar Junction Transistors (BJTs) ......... 24
      1.6.3 Integrated circuit fabrication and packaging . 25
   1.7 Radiation Effects ................................ 28
      1.7.1 Radiation Environment in Space ............... 28
      1.7.2 The total dose effects on electronic devices .. 39
      1.7.3 Enhanced Low Dose Rate Sensitivity of devices 40
   1.8 Conclusions ...................................... 42

2 Literature Review ........................................ 43
   2.1 Current mainstream radiation test methodologies .................. 43
   2.2 Current mainstream ELDRS testing methods ...................... 46
   2.3 Research in ELDRS .................................. 47
   2.4 Switching technique for accelerated ELDRS testing ............. 62
   2.5 Hydrogen soaking .................................... 64
   2.6 Current trends in spacecraft COTS technology .................... 67
   2.7 Conclusions from the literature review ....................... 68

3 Experimental Theory ...................................... 71
   3.1 Device Selection .................................... 73
3.2 Hydrogen Implantation of Devices ................................................. 80
  3.2.1 Theory of hydrogen implantation ............................................. 80
  3.2.2 Aims and requirements of hydrogen implantation experiment ........ 83
  3.2.3 Experimental design ............................................................... 84
  3.2.4 Predictions ........................................................................... 85
  3.2.5 Conclusions ................................................................. 85

4 Experimental Methods ................................................................. 86
  4.1 Implant Simulations ............................................................... 86
    4.1.1 Implant procedure .............................................................. 92
  4.2 Long term total dose irradiation experiment .................................. 105
    4.2.1 Experimental design .......................................................... 105
    4.2.2 Health and Safety considerations ......................................... 105
    4.2.3 Predicted results ............................................................... 106
    4.2.4 Conclusions ................................................................. 106
    4.2.5 Chamber design ............................................................... 106
  4.3 High dose rate tests ............................................................. 110

5 Results and Analysis ................................................................. 112
  5.1 Test Parameters and circuits .................................................... 112
  5.2 Results of Hydrogen ion implantation ........................................ 114
  5.3 Results of low dose rate irradiations ...................................... 115
  5.4 Results of high dose rate irradiations ..................................... 119
    5.4.1 AD590 ................................................................. 119
    5.4.2 LM124 ................................................................. 121
    5.4.3 Annealing ................................................................. 122
  5.5 ELDRS response ................................................................. 124
  5.6 Comparison with control samples ............................................ 127
  5.7 Comparison with published data ............................................. 129
  5.8 Criticisms ................................................................. 130

6 Conclusions ................................................................. 133
  6.1 Summary of results ............................................................. 133
  6.2 Investigating the role of hydrogen in ELDRS using ion implantation .... 134
6.3 Investigating hydrogen ion implantation on ELDRS susceptibility using high
and low dose rate testing ........................................... 137

6.4 Deriving a new accelerated test method for ELDRS ........................... 139
List of Figures

1. Photon attenuation coefficients with incident photon energy [MIT-10] ........... 22
2. The Bipolar Junction Transistor [HWSW-10] ........................................ 25
3. Proton flux >30MeV for ISS 30 day low Earth orbit [SPENVIS] ................. 29
4. Electron flux >1MeV for ISS 30 day low Earth orbit [SPENVIS] ................. 29
5. Annual dose from trapped protons, electrons and Bremsstrahlung radiation in SiO₂ within Al shielding [SPENVIS] ........................................ 30
6. Simulated proton flux along ISS orbit >30MeV for 24 hours [SPENVIS] ...... 31
7. Simulated electron flux along ISS orbit >1MeV for 60 hours [SPENVIS] ...... 31
8. Dose rates measurements from onboard the ISS over a >60 hour period by the DOSTEL silicon-based telescope during the DOSMAP experiment 2001 [BERG-08] 32
9. Proton flux for 20 day sun-synchronous orbit (>30MeV) [SPENVIS] .......... 33
10. Electron flux for 20 day sun-synchronous orbit (>1MeV) [SPENVIS] ......... 33
11. Dose from trapped protons, electrons and Bremsstrahlung radiation in SiO₂ within Al shielding (SSO) [SPENVIS] ................................. 34
12. Simulated electron flux (>1MeV) along SSO orbit for 1 orbit [SPENVIS] ...... 34
13. Proton flux (>30MeV) for 20 day MEO [SPENVIS] ................................. 35
14. Electron flux (>1MeV) for 20 day MEO [SPENVIS] ................................. 35
15. Dose from trapped protons, electrons and Bremsstrahlung radiation in SiO₂ within Al shielding [SPENVIS] ........................................ 36
16. Electron flux >1MeV over 24 hours in MEO [SPENVIS] ......................... 36
17. Proton flux >30MeV in GEO [SPENVIS] ............................................ 37
18. Electron flux >1MeV in GEO [SPENVIS] ............................................ 37
19. Deposited dose in SiO₂ due to trapped particle belts in GEO [SPENVIS] ...... 38
20. Simulated galactic cosmic ray ion spectrum for GEO [SPENVIS] ............... 38
22. ELDRS e- e+ effect in npn/pnp transistors [PEAS-09] .............................. 41
23. MPTB Accumulated Dose [TITU-98] .................................................. 48
25 MPTB Full Length LM124 Data [TURF-03] ..................... 50
26 Space-Charge Mechanism [FLEE-94] .......................... 52
27 Updated Space-Charge Electron Drift Model [WITC-98] ............... 53
28 Binary Reaction Rate vs Dose [FREI-98] .......................... 56
29 Binary Reaction Rate vs Time [FREI-98] .......................... 56
30 Passivation vs Stress [SHAN-02] .................................. 58
31 Passivation vs LM139 Input Bias [SHAN-02] ........................ 59
32 LM124 Passivation vs ELDRS Enhancement [SEIL-04] ............... 60
33 Packaging vs AD590 Output Current [PEAS-07] ...................... 61
34 Switched-Dose-Rate Schematic [BOCH-05] .......................... 63
35 LM139 Switched-Dose-Rate Results [BOCH-05] ...................... 63
36 Trends in device family testing from 2003 - 2009 at JPL test facility .... 67
37 Comparison between numbers of devices tested and numbers exhibiting HDR/LDR discrimination and ELDRS .......................... 67
38 AD590 Schematic [PEAS-07] ...................................... 74
39 AD590 Micrograph [PEAS-07] ...................................... 75
40 AD590 Metallisation diagram ....................................... 75
41 LM124 Schematic ................................................... 76
42 LM124 Circuit (1/4 LM124) .......................................... 77
43 Microscope image of LM124 .......................................... 77
44 Metallisation photomicrograph of LM124 (section inset) [SEIL-04] .... 78
45 SEM micrograph of semiconductor device structure. [YORK-10] .......... 80
46 SRIM plot for H ion deposition depth in semiconductor layers at 210 keV .... 81
47 SRIM plot for H ion deposition lateral spread in semiconductor layers at 210 keV .... 82
48 Implantation simulation of H into AD590 with Gold lid at 500keV [SRIM] .... 86
49 Simulation of H range in AD590 through Gold lid at 1.8MeV [SRIM] .... 87
50 Implantation simulation of H into AD590 with Gold lid at 1.8MeV [SRIM] .... 88
51 Implantation simulation of H into AD590 with Gold lid at 1.8MeV, transverse view [SRIM] ............................................. 89
52 Simulation of Damage Events from implanting H into AD590 at 1.8MeV [SRIM] 89
Nomenclature

ASTM American Society for Testing and Materials

BJT Bipolar Junction Transistor

Bq Bequerel

CMOS Complimentary metal-oxide-semiconductor

COTS Commercial off-the-shelf Technology

ELDRS Enhanced Low Dose Rate Sensitivity

ESA European Space Agency

eV Electron Volt

GEO Geostationary Earth Orbit

HDR High Dose Rate

Iib Input Bias Current

Ios Offset Current
ISS  International Space Station

JPL  Jet Propulsion Laboratory (US)

LEO  Low Earth Orbit

LDR  Low Dose Rate

MEO  Medium Earth Orbit

MOS  Metal Oxide Semiconductor

MPTB  Microelectronics and Photonics Test Bed

NASA  National Aeronautics and Space Administrations (US)

NPL  National Physical Laboratory (UK)

PETS  Pre-irradiation Elevated- Temperature Stress

RBS  Rutherford Backscattering Spectrometry

RGA  Residual Gas Analysis

SAA  South Atlantic Anomaly

SPENVIS  SPace ENvironment Information System

SRIM  Stopping and Range of Ions in Matter

SSO  Sun-Synchronous Orbit

TEOS  Tetraethyl orthosilicate

TSC  Thermally Stimulated Current

Vos  Offset Voltage
List of Tables

1  Device Test Results after Implantation ........................................... 114
2  AD590 Post-HDR Response after Anneal (Vout) ................................. 123
3  LM124 Post-HDR Response after Anneal Amplification (G=2) ............ 123
4  LM124 decapped control comparison (Amplification G=2) ................. 127
1 Introduction

Section 1 of this thesis will discuss the relevant background information required to understand the ELDRS (Enhanced Low Dose Rate Sensitivity) effect seen in bipolar devices. A description of the radiation environment experienced by a satellite in Earth orbit is described and a basic explanation for the origin of the radiation is discussed. A general overview of the effects of ionising radiation of matter is presented followed by a more specific review of the total ionising dose effects which present in modern electronic devices. The section concludes with the specific example of the ELDRS effect and results of experiments on irradiating susceptible devices are presented to illustrate the effect.

Section 2 consists of a literature review and critical analysis of the current mainstream radiation testing methodologies including the current proposed method for ELDRS testing. This is followed by a summary of the current state-of-the-art research being done in the field of total dose effects on the subject of ELDRS concluding with the acceptance of the presence of hydrogen within a bipolar integrated circuit correlating with ELDRS susceptibility. The section closes with a discussion of the current trends in spacecraft COTS (commercial off-the-shelf) technology, specifically those which are thought to be ELDRS susceptible.

Sections 3 and 4 propose a novel experiment involving the direct implantation of hydrogen within a device to probe the effect of hydrogen at differing locations and concentrations within a known ELDRS susceptible device. A discussion of the theory of hydrogen implantation and interaction is given alongside a description of the proposed experimental design. A description of a long term cobalt-60 based experiment is given which would act as a means of verifying results from the hydrogen implantation experiments by acting as a radiation test method specifically for ELDRS operating at low dose rates only. Predictions are presented for the outcome of these experiments followed by the testing methodologies.

Section 5 Consists of the experimental results and analysis

Section 6 Concludes this report with a summary of results and future proposals.
1.1 Motivation

The motivation for this research comes from the desire of the space industry to use commercial components. COTS technology is in a constant state of improvement with a product turnover much greater than purpose-built components. Commercial components are not necessarily built for the space industry and require testing before they can be used. Components of interest go through a rigorous selection routine before radiation testing takes place and due to the length of time and costs involved in selection and testing there is a desire to test quickly. Radiation testing of electronic devices is currently accelerated by increasing the dose rate to which the components are exposed up to the maximum total dose expected on the mission, this process allows a total dose that would during the mission potentially take years to accumulate to be deposited in a period of hours to days.

During the 1990s it was observed that electronic devices can react differently at very low dose rates when compared to the high dose rates used during normal accelerated radiation testing\[PEAS-98, JOHN-96, CHEN-00\]. It is possible for a device which appears to survive without significant degradation of function up to a set total dose at a high dose rate to experience total failure if the dose rate is decreased. This effect is known as enhanced low dose rate sensitivity (ELDRS). ELDRS is an emerging threat. Since 2010 the testing regimes for NASA and the European Space Agency have begun to include preliminary ELDRS testing. The most recent iteration of the MIL 883 1019.8 standard has included a section specifically for ELDRS testing, however this is not an accelerated method and currently requires the testing to be done at dose rate equal to that to be experienced during the mission, for the proposed length of time of the mission. Whilst this method may be acceptable for purpose-built industry components, it is unsuitable for COTS component which have a much quicker re-fresh time and could become obsolete during the testing period when using the current MIL 883 method\[BOCH-06, CHAV-06, DURA-07, HANS-07, HJAL-06, HJAL-08, KRIE-99, KRUC-08, KRUC-09, LOVE-07, MCCL-00, MCCL-03, PEAS-04, PEAS-06, PEAS-07, PEAS-09, SCHR-08, TITU-98, YUI-02\].

The components found to be susceptible are based on bipolar technology, and whilst some bipolar devices may be replaced by other components there are those which are irreplaceable and so testing is required. There is a desire to use commercial components, and as such there
is a need for an accelerated test method, ELDRS is a threat which renders the current total
dose radiation testing methods vulnerable to error when testing bipolar technology, thus there
is a need to investigate the ELDRS effect in order to produce an accelerated test for COTS
components which accounts for low dose rate sensitivity[YUI-02].

1.2 Objectives

The main objectives of this research are as follows:

1. To more qualitatively determine the effect of hydrogen in silicon-based devices susceptible
to ELDRS using ion implantation

2. To implant hydrogen into devices and study their response to irradiation using high and
low dose rate testing

3. To use the data from the hydrogen implantation experiments to develop a new accelerated
test method for ELDRS devices

1.3 Novelty

There are 2 areas of novelty in this project. Firstly the implantation of hydrogen into devices
for the purposes of ELDRS testing and secondly the design of a new accelerated test regime for
bipolar components using a hydrogen ion beam for sub-device level probing.

The first novelty comprises of the use of an ion beam to probe specific locations of a device
in order to give a deeper insight into the role of hydrogen in a devices response to radiation.
Unlike hydrogen soaking or exposing bare die to hydrogen, the method used in this thesis allows
for hydrogen ions to be implanted down to the transistor level of devices. Different areas on a
device can be implanted with hydrogen ions at varying concentrations without contaminating
areas outside that which is targeted allowing for future quantitative studies to be done on the
nature of hydrogen contamination in devices.

The second novelty is using the hydrogen ion implantation as part of a new accelerated
ELDRS test method. Current ELDRS test methods are either not accelerated or require long
term low dose rate tests for comparison and a large number of devices to be sacrificed for the
testing process. The method put forward in this thesis should not require low dose rate testing
and the number of devices used can consequently be reduced.
The combination of targeted hydrogen implantation and high dose rate cobalt-60 irradiation provides a novel approach to accelerated ELDRS testing of bipolar devices and for the first time permitting the probing of devices for ELDRS susceptibility at a sub-device structural level. These techniques can be used in the future to do further investigation into the interaction of hydrogen in devices and allow manufacturers to design devices which are intrinsically ELDRS-free.

The results of this PhD have shown that hydrogen ions can be implanted into specific regions of a device, and has established for the devices tested the upper and lower bounds for the concentration of ions which can be implanted without destroying the device. The results also confirm that below the minimum suggested concentration the implanted ions will be mobile and anneal out of the device at room temperature, whereas above the minimum they remain at the targeted location and do not contaminate adjacent areas.

It has also been found that the removal of device packaging changes the devices response to radiation due to hydrogen contamination from atmospheric exposure, at low dose rates de-lidded devices show a greater ELDRS response compared to unmodified samples and at high dose rates the devices can give misleading responses before annealing. It was found that the AD590 appeared to degrade less at high dose rates when the package had been removed, in contrast to the LM124, however after annealing the de-lidded electrical characteristics returned to their original level as opposed to the devices which had been implanted with hydrogen ions. ELDRS-free devices behave in a similar fashion to de-lidded devices and show more degradation when exposed to radiation at high and low dose rates once the packaging has been removed but the effect of hydrogen ion implantation is reduced to parameter offsets.

The developed accelerated ELDRS test method is put forward using high dose rate irradiation following probing with a hydrogen ion beam, several improvements and future suggestions are made to refine the method and it is recommended that a greater number and variety of devices are tested before it is accepted as a reliable method, in its current form it would be suitable for use during the manufacturing process for testing designs for ELDRS susceptibility by targeting specific locations in order to locate the susceptible regions for ELDRS due to hydrogen contamination, if used in this way it would allow for the creation of devices which were ELDRS-free regardless of packaging material.
1.4 Introduction to ionising radiation

Ionising radiation is a particle or electromagnetic radiation which upon interacting with a material has sufficient energy to liberate an atomic electron leaving the material with a change in charge. The Earth and space are constantly exposed to ionising radiation from both natural and artificial sources and the intensity and type of radiation varies depending upon location. The correct functioning of electronic components relies upon controlling the flow of charged particles through the materials they are composed of. When exposed to ionising radiation, additional charged particles are formed throughout the component which can disrupt normal operation. This section will introduce the key concepts of ionising radiation, its interaction with matter and specifically semiconductor devices, the radiation environment in space and modern semiconductor device physics.

The SI unit for energy is the Joule (J), for the discussion of radiation it is more convenient to use the established unit of the electron volt (eV) which is a measure of the energy required to accelerate 1 electron through a 1 volt potential difference, 1eV is equal to $1.6 \times 10^{-19}$ J. For a radiation to be ionising it needs an energy above 10eV as this is the minimum energy required to liberate bound atomic electrons thus leaving the atom in a charged, ionised, state. Typical ionising energy ranges are from 10eV up to 20MeV, although greater energies are possible in given high-energy circumstances such as particle accelerators. Nuclear instability, which leads to nuclear radioactivity, occurs in elements with a higher atomic number than Lead, 82. The larger the nucleus the more unstable. Radioactivity is a random process in that at any given point one cannot predict which part of the nucleus will decay, one can predict the rate at which the material as a whole will have a disintegration and this is known as the activity of the source, it has the unit of Bequerel (Bq) where 1Bq is one disintegration per second. The activity of the material should not be confused with the emission rate of the source (photons or matter) as this also depends on the structure of the source and location of each disintegration. Ionising radiation is often referred to as being either hard or soft, this is a reference to the ability of the emitted particle to penetrate a target material. The more penetrating the particle the harder the radiation. The hardness of radiation depends on the mass, charge, size and energy of the emitted particle. Radiation dose is the amount of energy deposited in a material per unit mass, it has
the SI unit of the gray (Gy) where 1Gy is 1 joule per kilogram. Traditionally, the “rad” unit is used, which can be converted into the SI unit through 1 rad being equal to 0.01 Gy; rad(Si) or rad(SiO2) can also be found in literature presented in this thesis, since the dose deposited in a material is depends upon both the characteristics of the radiation and the material, the material in brackets specifies the dose received in that particular substance when exposed to the specified source of ionising radiation.

Ionising radiation can be split into two groups, charged and uncharged particles. Charged particles include alpha, beta, proton and fast nuclei, uncharged particles are photons and neutrons. Each of these will now be discussed.

1.4.1 Charged radiation.

**Alpha particles**  An Alpha particle is composed of 2 protons and 2 neutrons, it is the nucleus of a Helium atom. Due to its size and charge it strongly interacts with materials, it is highly ionising however for these reasons it cannot penetrate deep into materials. Alpha particles escape heavy nuclei via quantum barrier tunnelling and are observed to typically have energies between 4 MeV and 6 MeV, alpha emitters exist below and above these thresholds however the half life of an alpha emitter below 4 MeV is very large and above 6.5 MeV an alpha-emitting element will decay by half in a matter of days. Typical ranges for alpha particles are 50mm in air and 23\textmu m in Silicon.

**Beta particles**  Beta particles are either electrons with a negative charge or their antimatter equivalent, positrons and are denoted by $\beta^-$or $\beta^+$. Beta particles are formed from the conversion of a bound neutron into a proton, electron and neutrino. Since the electron is much lighter than an alpha particle it is easily deflected and due to the particle velocity approaching the speed of light these particles are themselves only lightly ionising. When beta particles change direction or are stopped within a material energy is conserved through the release of bremsstrahlung radiation which are photons, which may then themselves cause further interactions within a material.
Protons  Protons can be described as free Hydrogen nuclei, have a positive charge and are 1836x more massive than a beta particle. At energies in the MeV range, protons can travel in the order of centimetres in air and tens of microns in Aluminium. Due to their mass they are much harder to deflect than beta particles however due to their high reactivity with matter they react immediately if created in nature unless confined in a magnetic field.

1.4.2 Uncharged radiation.

Neutrons  Neutrons are slightly more massive than protons but carry no charge, they are therefore very difficult to stop as are unaffected by electromagnetic repulsion, slow neutrons have energies of the order of eV which is gained through thermal excitement whereas fast neutrons can have energies above 100keV. Due to the similarity in size between neutrons and protons, hydrogen and water are often used to slow fast neutrons. When neutrons impact a nucleus the resultant energy is often released as a gamma ray.

Photons  Photon radiation can be split into X-rays and gamma rays. Both forms of radiation are photons and both interact by the same mechanism. The difference between them are their origins. X-rays are formed from the rearrangement of atomic electron shells whereas gamma rays are formed from nuclear energy transitions. Photons are lightly ionising, highly penetrating and leave no residual activity in a target material. X-rays can be produced via charged particle collisions, whilst gamma rays tend to follow beta decay. A beta decay can leave the produced, daughter, nuclei in an excited state, the gamma energy released from the nucleus settling into its lowest state corresponds to the energy level transitions of the daughter nucleus, whilst the half life, decay rate, quoted for a source will relate to the parent nuclei. Gamma rays formed following beta decay typically have energies less than 2.8 MeV, and up to 9 MeV from neutron capture. Photons can be found from a few eV to GeV in extreme environments in nature- such as gamma ray bursts from supernovae, and will interact with matter according to their energy and the density of the target material regardless of their origin.
1.5 The effects of ionising radiation on matter

Below is a summary of the basic interactions between ionising radiation and matter covering the well known and established principles behind the interactions.

There are two primary ways in which the discussed ionising radiation will interact with matter, the first is ionisation and the second is ballistically.

Photons, whether from X-rays or gamma rays act via ionisation. There are three mechanisms available to the photon upon entering the coulomb field of an atom, compton scattering, the photoelectric effect and pair production, highlighted in Figure 1.

1.5.1 Pair production.

Due to the interchangeability of matter and energy, the masses of electrons can be expressed as energy, 511keV. If an incident photon has greater than twice this energy, 1.022MeV there is a probability, then when within the coulomb field of an atom, this photon will spontaneously be replaced by an electron and it’s antimatter counterpart, the positron. These particles will share the remaining energy of the photon as kinetic energy. The likelihood of pair production occurring increases the higher the incident photons energy above 1.022MeV. Unless under the influence of an applied electric field the two particles will recombine and release two annihilation photons to satisfy the conservation of energy.

1.5.2 The photoelectric effect.

An incident photon may be completely absorbed by a bound atomic electron in the target material, usually in the K-shell which can provide the electron sufficient energy to enter into an excited state at a higher energy level, or to escape completely leaving the atom with a net positive charge, thus in an ionised state. The remaining bound electrons will reconfigure to fill the K-shell vacancy and in doing so release a photon with an energy equal to the difference between the K-shell and rearranged electron level, this photon is known as a characteristic X-ray as it can be used to identify the element from which it was emitted.
1.5.3 Compton scattering.

An incident photon is described as scattering with an electron, a fraction of the energy of the photon is transferred to the electron, there is a continuum of possible energies which can be transferred, the photon is deflected away and the electron recoils. Compton scattering is directly proportional to the number of electrons per unit mass, is independent of the atomic number of the incident material and the probability of scattering decreases inversely with photon energy.

The outcome of these three processes are the release of electrons within the incident material, and the subsequent formation of ‘holes’ which are the local positive charge caused by the removal of an electron.

A heavy charged particle, such as a proton or alpha particle may pass through a target material given sufficiently high energy. As the charged particle moves through the material it attracts the bound negatively charged electrons, this coulombic force can supply enough energy to raise the electrons to excited states or to provide enough energy for the bound electrons to escape their parent atom. This process leaves a funnel of electrons and subsequently positively charged atoms (holes) along the path of the incident particle. These fast moving free electrons are often referred to as Delta rays.

These Delta rays, and indeed beta radiation will interact via coulombic processes in the incident material, repulsed and backscattered from bound electrons and attracted to the positive charges, electrons are readily absorbed into a target material releasing energy as bremsstrahlung radiation with each change in acceleration.

Figure 1 shows the interaction cross-sections for the photoelectric effect ($\sigma=\tau$) and pair production ($\sigma=\chi$) for varying photon energies ($hv$) at different atomic numbers ($Z$) for the absorbing material.
1.5.4 Ballistic interaction

A ballistic interaction, or atomic displacement is where a heavy charged particle (or very energetic photon) is incident on an atom and provides enough energy to dislocate the atom from it’s position in the material. In a crystal structure this will leave a vacancy (referred to as a Schottky defect), which may be left empty or filled by a neighbouring atom creating what is referred to as a Frenkel pair. In some circumstances this may be unnoticed, but if this crystal is being used to conduct electricity in a controlled manner then atomic displacement becomes an important issue. Another form of defect caused by ballistic interaction leads to an atom being located in a previously unoccupied region of the lattice which may lead to structural and electrical destabilisation, these are interstitial defects. In bipolar technologies where the amount and arrangement of dopant atoms in a semiconductor is critical to the correct functioning of the device, these ballistic interactions are both key to the initial implanting of dopants in the semiconductor material and subsequently to device breakdown when subjected to further undesired displacements during exposure to particle radiation.
1.6 Semiconductors

When speaking of conductivity, materials can be split into four groups. Metals, semimetals, semiconductors and insulators. In a conductor the energy levels between the conduction and the valence band overlap, where the conduction band is marked by the highest energy level of a bound electron and the lowest energy of the valence band is marked by the energy required for an electron to be freed from its parent atom. It is for this reason that metals are said to have free electrons. In an insulator the conduction and valence band are separated such that at room temperature when exposed to a low electric field no current will flow. Current will eventually flow if the potential is great enough, this is often known as dielectric breakdown and the level required will vary depending upon the material. In a semiconductor the difference between the valence band and the conduction band, the band-gap, is small enough that electrons supplied with the order of 10eV may cross from the valence to the conduction band. Silicon is a semiconductor at room temperature, it has four electrons in its outer most shell and thus can accept a further four from neighbouring atoms. When silicon is grown it forms a very tight crystal lattice with each atom sharing 1 electron for each of four neighbours to complete its outer shell. Foreign elements are added to silicon in order to provide extra free charges. A Group III element such as Boron can be added in place of a silicon atom into the crystal structure of the order 1 Boron atom per 10⁶ Silicon atoms. Boron has one less electron in its outer shell which constitutes a ‘hole’ in the lattice into which electrons from the Silicon atoms can move. As the electrons move into this hole it is said to ‘move’ through the lattice. Likewise a Group V atom can be added which will add an extra electron to the lattice which is free to move. This addition of foreign elements is known as doping, when a Group III element is added it is known as p-type since there is an extra positive charge, Boron is used as a P-type dopant, it has a hole which sits just above the Silicon valence band. For silicon alone the gap between the valence and conduction band is 1.12eV however only 0.045eV is required to ionise the Boron thus lowering the band-gap of the composite. Phosphorous, which is a Group V element can be added which has a similar effect whereby its additional electron has an energy level just below the conduction band for Silicon. This is known as n-type doping.
1.6.1 The PN junction

When a piece of n-type Silicon is placed in contact with a piece of p-type Silicon a junction is formed. The p-type has a surplus of positive holes and the n-type has a surplus of negative electrons (it should be noted both are electrically neutral since the extra charges are countered by the nuclei of the dopant atoms). Holes from the p-type drift towards the n-type Silicon and electrons towards the p-type, subsequently the holes neutralise the electrons near the interface of the n-type and electrons fill the holes near the interface in the p-type silicon. This process creates what is referred to as a depletion region, where at the junction between the two counter-doped Silicon crystals the free charges are neutralised and atoms on either side are left ionised due to the removal of charge. Applying an external electric field, with the negative charge at the n-type silicon and positive at the p-type, electrons move from the n-type to the p-type region and holes move in the opposite direction, current flows through the junction. This is also known as ‘forward biasing’. Reverse, or ‘back biasing’ is the opposite, electrons and holes flow away from the depletion layer thus widening it and no current can flow. This is the fundamental operation of a diode.

1.6.2 Bipolar Junction Transistors (BJTs)

A bipolar junction transistor is made from three layers of doped Silicon. Either NPN or PNP, which determines what the majority charge carriers will be. In a PNP transistor, holes are the majority charge carrier and electrons in an NPN transistor. In both transistors there are three sections, the collector, base and emitter. The emitter is moderate in size and heavily doped, the base is thin compared to the emitter and base and lightly doped and the collector tends to be largest as it is required to collect most of the charge from the emitter. As with a diode, placing n-type silicon next to p-type creates a depletion region. In a bipolar transistor there are two junctions, one between the collector and base and the second between the base and emitter, both of these junctions form depletion regions. If the emitter-base junction is forward biased, the majority carriers flow from the emitter to the base and current will flow between the emitter and base, there is some recombination but since the base layer is thin and only lightly doped this is small compared to the charge flowing from emitter to base. By reverse biasing the collector-base
junction charge will continue to flow from the emitter to the base, known as the base current $I_b$, however a large current will flow from the emitter to the collector, this is known as the collector current $I_c$. The base and collector current are related through the emitter current such that $I_e = I_b + I_c$. In this way the transistor can act as an amplifier since a small current at the base enables a large current to flow at the collector. The transistor can also be operated as a switch whereby the current applied to the base will either allow or prevent a current to flow from the emitter to the collector. Figure 2 shows the functioning of an NPN transistor and the relevant current flows. [SZE-02]

![Figure 2: The Bipolar Junction Transistor](HWSW-10)

1.6.3 Integrated circuit fabrication and packaging

The fabrication of integrated circuits involves the repeated deposition and etching of masked layers of conductors and insulators on silicon-based wafers before being packaged in either a metal, ceramic or plastic protective container.

**Fabrication** The first stage is the growth of a silicon ingot. A crystal of pure silicon is lowered into a container of pure molten silicon, this crystal acts as a seed and as it is drawn out of the container a large silicon ingot in the form of the seed is grown around it. This silicon ingot is ground smooth in water and sliced into individual wafers. These wafers are then ground smooth followed by a series of rinses and etches to remove any surface contamination before being polished. The wafers are then cleaned in hot acids, hydrogen peroxide, hydrochloric acid, sulphuric acid and ammonium hydroxide before being thoroughly rinsed in deionised water and spun dry in a nitrogen atmosphere. The wafers are placed into an oven in an oxygen rich atmosphere which encourages the growth of silicon dioxide on the surface which protects
the silicon from reacting with the air in the laboratory. A photoresist which has been mixed with a solvent is poured over the wafers, the wafers are baked in an oven until the solvent has evaporated leaving a layer of photoresist on the surface of the SiO$_2$. A chrome plated glass mask is placed over the wafers which are then exposed to ultraviolet light. This process is known as photolithography. A negative photoresist will harden when exposed to UV light whilst a positive photoresist will soften when exposed. The mask is removed and the wafer is washed in acid to etch away the soft photoresist, or a dry etching method using an oxygen/fluorine plasma depending upon the precision required (plasma etching provides sharper edges). The exposed SiO$_2$ can then be etched away thus exposing the bare silicon beneath and the hardened photoresist is removed using a plasma and hot acid bath. A further thin layer of SiO$_2$ is grown above the exposed silicon. Dopant atoms can now be implanted, usually boron, phosphorus or arsenic depending on the type of doping required, p-type or n-type. The thin SiO$_2$ layer allows the ions to pass through into the silicon beneath however the thick SiO$_2$ prevents the implanted atoms reaching the silicon which allows for the formation of isolated areas of doping which are required for creating the PN-junctions necessary for bipolar transistors, the SiO$_2$ is also used to isolate the n-type and p-type regions from one another. The wafer is then placed in an oven to anneal which expands the doped regions. A further protective layer of SiO$_2$ is then deposited over the entire wafer surface. In a deposition furnace, silicon nitride is deposited on the surface of the SiO$_2$ layer which prevents it from growing any further. A mask is then applied and acids are used to etch both the exposed nitride and the SiO$_2$ beneath down to the silicon. The process of doping and etching and adding protective layers continues until all necessary dopants have been added in the required regions for the transistor(s) to function, this process is typically repeated 12-25 times. Once doping is complete, a thick layer of SiO$_2$ is grown, this layer is often referred to as the ‘Field Oxide’. This layer is grown in an oxidation furnace which exposes the silicon to oxygen using a mixture of oxygen and hydrogen as steam. This steam process facilitates the growth of a thick layer of SiO$_2$. Any further nitride layers can be removed using a combination of dry (plasma) and wet (acid) etching and if required further implantations can be carried out over the thin oxide layers. Polysilicon, which consists of small grains of silicon which can be doped to improve conductivity, is deposited, followed by a mask and dry etching to form internal electrodes. Once made the entire wafer is washed and annealed. A further layer
of SiO₂ is grown and then polished until the surface is even. Plasma is used to etch through points in the SiO₂ so that the electrodes can be plugged with tungsten to ensure an electrical connection between the transistors and the internal wiring. An aluminium-silicon or copper alloy is deposited and dry etched using a mask to form these first wires. Several layers of wiring may be required thus this process can be repeated many times depending upon the complexity of the integrated circuit design. Finally a passivation layer, such as silicon nitride, is deposited to protect the surface from interacting with air, this nitride is etched away only above the bonding pads which are used to connect the circuit to external pins once packaged.[MCCL-12, STON-01]

Packaging  The wafers are cleaned and split into separate chips after being tested for defects. These chips are sorted and washed in deionised water and then dried before being attached to packages. Die attach, which can be solder or a silver filled epoxy or cyanate ester blends, is applied to a lead frame using computer controlled syringes. This substance is used to secure the chip in position. This frame, which is finished with either tin-lead solder or a nickel-palladium coating, is placed in either an epoxy or ceramic base depending upon the desired package. If the device is to be hermetically sealed, a silver-filled glass or gold-silicon eutectic is used to attack the chip die to the substrate base. The lead frame/substrate base has contact points for external pins from the device, gold or silver wires are soldered from the exposed pads on the chip to these contact points before being encapsulated. A ceramic package will have its lid and based made from pressing ceramic powder into a mold and then encasing the chip on the lead frame, whilst a plastic encapsulated package will be held in a mold which is subsequently filled with a liquid resin which sets. Once sealed the devices are trimmed and formed to shape with any excess mold compound removed. Finally manufacturer markings are added to the lid of the device before final inspection and testing.[CHEN-12][LUTZ-11]
1.7 Radiation Effects

There are three sources of ionising radiation in Earth orbit which affect spacecraft, these are the trapped particle belts, galactic cosmic rays and solar events. The trapped particle belts are formed through a process whereby neutrons are freed from the upper atmosphere by incident cosmic rays, these free neutrons then decay into protons and electrons which in turn become trapped in the magnetic field of the Earth. The damaging region of the outer belt which consists of electrons with energies greater than 1MeV extends to approximately 7 Earth radii, the minimum altitude for a damaging region of the radiation belts occurs at approximately 500km over the southern Atlantic region, this is a localised distortion known as the South Atlantic Anomaly[UNDE-94, UNDE-96, HARR-08].

1.7.1 Radiation Environment in Space

It is necessary then to be able to predict the radiation environment in space correctly in order to develop an accurate test regime in the laboratory. To this end a number of simulations of the radiation environment around Earth have been produced describing the radiation flux and the dose composition at a selection of orbits.

A software tool from the European Space Agency called SPENVIS (SPace ENvironment Information System) (www.spenvis.oma.be/spenvis) has been used to simulate the radiation dose for 4 representative orbits, a LEO (Low Earth Orbit) mission, a MEO (Medium Earth Orbit) mission, sun synchronous (SSO) and geostationary (GEO) satellite. The data for the LEO mission is discussed in this section.

Spenvis uses the industry standard AP8 and AE8 models for trapped protons and electrons respectively and these models can be set to represent either high or low flux depending on the current solar cycle. Simulating the deposited dose in material used the standard SHIELDOSE-2 model within SPENVIS which allows the simulation of dose deposited from trapped radiation in the simulated orbit within a chosen material (in this case silicon/silicon dioxide) through set layers of aluminium shielding.
Low Earth Orbit, ISS  

Figures 3 and 4 show the radiation environment in terms of damaging proton and electron flux throughout the orbit of the ISS (International Space Station). The simulation was allowed to run to represent a period of 30 days in order to build up a map of the region around the South Atlantic Anomaly where the damaging flux is at its greatest. The remainder of the simulations are set to a period of 60 hours to aid comprehension. The dark area shows the simulated path of a satellite which does not cover the polar regions, the area in
which the colour changes indicates an increase in the trapped particle density above the flux set for each chart. In Figure 3 this is focussed around the South Atlantic in circular fashion which increases in intensity towards the centre. The electron flux in Figure 4 shows an extension of the region from Figure 3 and an additional region of high electron flux towards the North.

Figure 5: Annual dose from trapped protons, electrons and Bremsstrahlung radiation in SiO$_2$ within Al shielding [SPENVIS]

Figure 5 displays the dose deposited in SiO$_2$ from the trapped particle belts. As can be seen the electron dose tails off quickly with an increase in thickness whilst the heavier, and so more penetrating, protons pass through with shielding having little effect. The Bremsstrahlung radiation is a secondary source formed within the material and shielding from the incident particles.
Figures 6 and 7 show the predicted proton and electron flux at the ISS for a period of 24 hours around the orbit, this amount of time ensures it will have passed through the SAA (South Atlantic Anomaly) and this can be seen by the sudden increases in flux each day. The proton flux is calculated only when the proton energy is greater than 30 MeV since below this energy the penetrative power will be reduced to the point where there is little measurable effect within a device, and above this energy the proton begins to have sufficient energy to pass straight through shielding and devices relatively unaffected and so depositing little dose. This is similar to electrons however the threshold energy is at above 1 MeV.

It would be expected from knowing that there is always an increase in ionising particle flux
from both protons and electrons when passing through the SAA (and indeed other areas shown to have increased flux) the deposited dose, and hence dose rate, would be increased. Conversely, when a craft leaves an area of high ionising particle flux one would expect the dose rate to decrease significantly. Figure 8 shows dose rate measurements taken onboard the ISS for the same period simulated in previous figures.

Figure 8: Dose rates measurements from onboard the ISS over a >60 hour period by the DOSTEL silicon-based telescope during the DOSMAP experiment 2001[BERG-08]

Figure 8 [BERG-08] compares well with the assumption that increased flux from the SAA as simulated using SPENVIS leads to an increase in measured dose rate on board the spacecraft. There are 2 main features to this graph, the first is the low fluctuations in dose rate due to galactic cosmic rays, and the much larger repeated peaks which occur when the ISS passes through the SAA. The consequence of this is that the dose rate is not constant over time within the craft. It varies each hour with the galactic background and it varies greatly each day by almost two orders of magnitude when the craft passes through areas of high particle flux. Total dose data from KITSAT-1 when compared to the SPENVIS predictions has shown that the dose rates predicted by SPENVIS are approximately a factor of two higher than those measured but still compare well[UNDE-96].

**Sun Synchronous Orbit**  Modelled on the Hinode (SOLAR-B) solar telescope.

Altitude: 686km
Figures 9 and 10 show a similar distribution of flux to figures in the previous paragraph. Both are low Earth orbits, however the SSO is at an altitude in which it not only interacts with the SAA but also the trapped electron belt which is why there is an increased flux at high and low latitudes.
Figure 11: Dose from trapped protons, electrons and Bremsstrahlung radiation in SiO2 within Al shielding (SSO)[SPENVIS]

Figure 11 shows the deposited dose in silicon dioxide from the trapped radiation belts through layers of shielding. 1cm brings the dose from electrons and consequently Bremsstrahlung down to approximately 1cGy, whilst the dose from the trapped protons continues relatively unaffected by shielding. As shown in figure 13 the proton dose only occurs during the crafts passage through the SAA.

Figure 12: Simulated electron flux (>1MeV) along SSO orbit for 1 orbit [SPENVIS]

Figure 12 shows the time dependence on flux and hence dose along the SSO over the period of a single orbit. The proton flux is intermittent as expected, the electron flux is also intermittent but to a lesser extent. During a 24 hour period there is approximately 5 hours between proton
induced dose the dose from electrons has less than an hour between fluence events allowing little
time for recovery.

**Medium Earth Orbit** Modelled on the GIOVE-A spacecraft

Altitude: 23916km

Inclination: 56 degrees

Figure 13: Proton flux (>30MeV) for 20 day MEO [SPENVIS]

Figure 14: Electron flux (>1MeV) for 20 day MEO [SPENVIS]

Figures 13 and 14 indicate that the craft is in an orbit which places it outside the proton
belt, as in Figure 13 there are no positive values present, and within the electron belt with an
almost constant high electron dose being received aside from at the extremes of latitude. Figure
14 shows an increase in electron flux towards the equator which decreases to below the threshold at the extremes of the orbit.

Figure 15 shows there to be no proton dose contribution to the total deposited dose. The electron dose tails off after 1cm of Al shielding however the induced Bremsstrahlung radiation continues to the order of 100cGy regardless of shielding up to 2cm.

The electron flux does have periods of low intensity for approximately 2 hours periodically which could allow for some recovery of devices, however the flux (hence dose) rates are very high when passing through 0 latitude every 8 hours, as shown in Figure 16. The regularity of the
variation in flux described here only relates to the radiation dose associated with a spacecraft passing through the radiation belts and does not include dose deposited by solar events which are less predictable.

**Geostationary orbit**  Modelled on the GOES system

Altitude: 35790km

Figure 17: Proton flux >30MeV in GEO [SPENVIS]

Figure 18: Electron flux >1MeV in GEO [SPENVIS]
Figures 17, 18 and 19 show a high electron dose and that at this altitude all the dose is received at a single point during the orbit as opposed to a continuous dose throughout from the radiation belts. Figure 18 shows there is still a measurable electron flux within the shielding at a single point at 0° latitude and +100° longitude.

There is another source of radiation which affects spacecraft at this altitude, galactic cosmic rays. The spectrum of galactic cosmic rays for this orbit is shown in figure 20.

Figure 20 shows the flux of galactic cosmic rays (accelerated ions) at GEO altitude. The peak fluence is shown to be approximately 2000 H ions per m², per steradian per second at an energy of almost 1000MeV per nucleon. Galactic cosmic rays, and solar particle events are a concern
when dealing with single event effects as a great amount of energy is immediately deposited in a very small area, which in turn contributes to the total dose experienced by the device, both galactic cosmic rays and solar particle events contribute significantly to ionising dose in GEO.

1.7.2 The total dose effects on electronic devices

Radiation effects on electronic devices can be split into two categories, single event effect and total dose effects. Single event effects are immediate, a source of radiation will interact with the electronic device and there will be an immediate measurable effect in the output of the device, be it a flipped bit or complete latch up and failure of the device. Total dose effects are not prompt effects, they can be described as a gradual degradation of electrical functionality of a device due to the cumulative effect of exposure to ionising radiation[HAUG-06, KRUC-09, UNDE-96, SUTT-05].

At this point it would be appropriate to describe the structure of typical semiconductor devices. Figure 21 shows the typical structure of a variety of semiconductor devices and illustrates the structural similarities between them.

![Figure 21: Structure of modern semiconductor devices [AERO-10]](image)

The physical changes of a device due to total dose damage have been described previously. Atomic dislocation caused by particle and high energy photon radiation alters the structure of the crystal lattice which constitutes the bulk of a semiconductor, potentially adding extra defect sites. Addition effects within the device lead to ionisation and charge trapping. The consequences of both atomic dislocation and ionisation are changes in the interaction between
the semiconductor material and the charge carriers in use. The carrier lifetime and mobility can be reduced leading to charge buildup within a device, charge can also become trapped in the semiconductor layers, all of which manifest as changes in the electrical characteristics of the device under irradiation. These characteristics vary depending on the structure and use of the device[BELY-95, BOES-90, CHEN-05, CHEN-07, CHEN-81, FLEE-94, GRUB-98, HAYA-07, RASH-02, RASH-03, ZEBR-05, ZEBR-06].

1.7.3 Enhanced Low Dose Rate Sensitivity of devices

A total dose effect of particular interest is the tendency for bipolar devices to show an enhanced sensitivity to low dose rates. A device may appear to decrease in functionality with increased radiation dose, that is, shows a positive correlation between damage and dose, and by extension, damage and dose rate. However it has been found that bipolar devices can have a much lower total dose failure when irradiated at low dose rates (below 10mGy(Si)/s) than when irradiated at the dose rates currently used in standard accelerated tests. Devices known to be affected include voltage references, operational amplifiers, sample and hold amplifiers, voltage comparators and digital-analogue converters[KENN-09, PRIT-03, VELO-10]. Figure 22 shows the response of ELDRS-sensitive devices to differing rates of irradiation and demonstrates the ELDRS effect. The most sensitive parameter on each device has been measured after being irradiated at, keeping with the units in the figure, 50rad(Si)/s, the devices were then irradiated to the same total dose at lower dose rates and the damage (parametric change) normalised to the value measured at 50rad(Si)/s. Figure 22 is showing that as the dose rate used to irradiate the devices was decreased, the relative damage to the device increases significantly.
Particular issues with the ELDRS effect include the differing electrical response depending on the device, in that in one device the ELDRS effect manifests as an increased bias voltage at low dose rates, whilst another may show gain degradation [PEAS-09]. This implies that the differing structures of semiconductor devices have an effect on the manifestation of ELDRS, potentially meaning that if the shape of the oxide is changed in a device through an altered manufacturing process, for example birds-beak oxides replaced by isolation trenches, the device would have to be re-tested. Additionally, the presence of ELDRS in devices can vary between manufacturer. It has been noted that whilst one set of devices from one manufacturer appear to be free from ELDRS, the same device from another manufacturer can exhibit ELDRS. This then implies that differing manufacturing processes may affect the susceptibility of a device to ELDRS.

Finally it is also unknown whether there is a threshold level at which the enhanced sensitivity of a device begins, if a hypothetical device can survive up to 150Gy at 10Gy/s, but is susceptible to ELDRS such that it fails at 15Gy when dosed at 5mGy/s, it is not currently predictable whether or not one may find if at 0.05mGy/s the device can survive to 150Gy again or perhaps fail at an even lower total dose. The main reason for this unknown is that at extremely low dose rates- approaching nominal background radiation on Earth it would take decades for the
total dose to reach an appreciable amount [TITU-99, UNDE-96, UNDE-94, MESH-04, NOWL-05, NOWL-94, HARR-08].

1.8 Conclusions

Spacecraft in any orbit are subjected to radiation from either trapped radiation belts, solar particles, galactic cosmic rays or all three. The radiation environment in the trapped particle belts and galactic cosmic ray background are well known and we have models to predict the typical dose rates using software simulation. The solar events are less predictable but do follow an 11 year solar cycle of magnitude and frequency [HARR-08, TITU-99, UNDE-94, UNDE-96].

This ionising radiation affects matter either through direct ionisation or through physical damage as with atomic dislocation, there are also secondary interactions between radiation and incident matter which contribute to the total dose deposited. In spacecraft electronics these radiation effects are split into immediate single event effects and total ionising dose effects. Total dose effects are changes in the electrical properties of a device due to cumulative radiation damage, this cumulative damage manifests itself as gradual changes in the electrical operating parameters of the device until eventual failure [CHEN-00, HAUG-06, NOWL-94, SUTT-05].

A type of total dose effect experienced by bipolar devices is an enhanced sensitivity to dose rates below 10mGy(Si)/s which is the typical minimum dose rate used for testing. It is not fully understood why some devices are susceptible to ELDRS where others aren’t, it is thought to be related to the structure and manufacturing methods used in constructing the semiconductors. The devices affected fail at a significantly lower total dose when irradiated at low dose rates than when irradiated at dose rates much higher than those typically found in standard Earth orbits [FLEE-06, KRIE-01, POSE-04, SHAN-02, SHAN-03, SHAN-06, PEAS-09].
2 Literature Review

2.1 Current mainstream radiation test methodologies

There is currently no single unified testing regime for ionising radiation testing in the space industry, the three most widely used regimes are the European ESA-SSC 22900 [ESA-2290], the American Military standard MIL 883 1019.8 [MIL-883] and the private sector ASTM standard [ASTM-12]. Of the three, the ESA and MIL 883 are the two most widely accepted standards- in that they are adapted by smaller organisations, and are almost now equivalent in procedure[KENN-09, RIVA-04, MANG-04, MESH-04, NOWL-05, PEAS-91, PRIT-03].

There are other test method series which deal with high energy radiation tolerance testing, which tests the response to pulsed, total dose and neutron radiation. Whilst thorough, these testing methods are aimed mostly at the military use of semiconductors in very high dose environments such as nuclear weapons and delivery vehicles and so the testing range is very different to that required for most space missions.

The ASTM (American Society for Testing and Materials) method follows a similar regime to that of the latest MIL 883 1019.8 radiation testing method but appears to concentrate on neutron radiation to study bulk damage in semiconductors, followed by studying the absolute absorbed dose using electron beams, after which the remainder of the procedure compares well with the MIL/ESA regimes in using a cobalt-60 source for gamma-ray irradiation testing.

A simplified process representing the ESA/MIL standards is presented below[MIL-883].

1. Give serial numbers to each test sample: Each device is given an identifier to indicate the type of device, the batch and/or manufacturer, test details and in some cases the date.

2. Perform an electrical test of nominal operating parameters: This is to initially characterise the device, it would record parameters such as the current drawn, input bias, test signals through the input/output pins, where applicable test process are run, for example for memory devices a series of write/read test patterns. The operating parameters are measured and compared with values supplied by the manufacturer where available.

3. Irradiate to specified dose (or in steps with tests (ESA)): The length of irradiation time would depend on the radiation source strength and the required dose, typically hours.
some cases a total dose is given and the device is irradiated in stages up to this point and at the end of each stage the device has similar electrical tests performed which aids in determining the speed of its degradation and better map the changes in the electrical characteristics. During these interim tests the device is typically not being irradiated.

4. Room temperature anneal under bias: A bias is applied and the device left for a number of hours (168 ESA) at a controlled room temperature to allow defect migration and potentially some unaided restoration of electrical properties.

5. Perform over-test if appropriate: In some situations if the device is still functioning one may wish to test above the specified dose to account for situations where the device may be exposed to an increased amount of radiation. If this is unlikely then an over-test is generally avoided as it highly likely it will result in the complete destruction of the device, thus further testing is impossible.

6. Accelerated ageing via annealing under bias (\textasciicircum 100^\circ\text{C}): Annealing is used to simulate ageing through the disassociation of defects within the semiconductor bulk. Defects associated with different elements will ’anneal out’ at different temperatures and it is possible to characterise defects by recording the change in electrical properties of a device with increased temperature.

7. Repeat initial electrical tests: An identical set of tests are performed as in the pre-irradiation phase and if the device is still functioning the new operating parameters are recorded. The change in these parameters can then be analysed with the intention of formulating the predicted lifetime of the device under irradiation when in space and the expected electrical responses to aid in mitigation methods (taking account of an increasing input bias, compensating for more leakage current etc).

8. Determine pass or fail: If the device is damaged beyond reasonable repair, in that it could not be repaired remotely when on-board a satellite, or the device would survive the environment but not for the required length of time for the mission then it is counted as a failure. Statistical analysis of the results aid in determining whether the device tested, acting as a representative of the batch, passes.
Annealing simulates the ageing of semiconductors as the application of heat over short periods of time (compared to the length of a space mission) causes defects to propagate within the semiconductor as would naturally occur over its lifetime. This is one effect noted in aged semiconductors, it does affect the electrical properties and so is important however it does not take any other factor into account such as damage caused by the act of heating and cooling the device during testing. ELDRS is an unexpected effect which demonstrates that for certain devices (mostly bi-polar technology[PEAS-09]) a high dose of radiation over a short amount of time does not equal the radiation induced ‘ageing’ damage sustained in practice, as such it would be prudent to assume until proven otherwise that annealing over short periods, whilst simulating one effect of an aged semiconductor, may not simulate all the effects necessary to fully characterise a device in that it may not determine whether the device is susceptible to ELDRS[BOCH-01]. This could be tested by performing a series of irradiations on identical devices and then annealing at different temperatures for a set amount of time and comparing with a control device kept at nominal temperature for an extended period- and thus allowed to age normally (there is a method in use similar to the method described here which is known as “step-stress’ however this method does not compare different temperatures). The results could then be compared to test for correlation between the altered electrical properties after high temperature anneals and ageing. This procedure could be used when investigating ELDRS susceptible devices to verify whether annealing at increased temperature is a viable method for simulating ageing after another variable has been altered.

Cobalt-60 produces two gamma ray emissions at 1.33MeV and 1.17MeV. The 1.33MeV ray is enough to incite pair production (electron-positron) within electronic devices which themselves will cause the typical damage described earlier. However, the energy spectrum of incident radiation whilst in orbit is over a significantly wider range [UNDE-96, HARR-08] and whilst these levels are enough to simulate some radiation damage it may be prudent to test over a wider variety if only to verify that cobalt-60 is sufficient. There has already been research done in this area [NOWL-94]however the precise effect of bulk damage on ELDRS susceptibility has yet to be thoroughly characterised since the sources used in current radiation testing only cause ionisation and the energies used are insufficient to cause significant displacement effects.

The process of annealing and irradiating over short periods of time as described in the
current testing method assumes the dose rate does not change over the length of a mission, or at least any change is inconsequential. We know that cosmic ray flux changes regularly, varying with the solar cycle[UNDE-96, BERG-08]; during periods of increased solar activity the higher energy galactic cosmic ray incident flux decreases and the trapped concentration increases, as does the probability of a coronal mass ejection which can temporarily flood an area with high energy electrons and protons. The rate of solar events varies in frequency over roughly an 11 year cycle, additionally during the orbit of a craft the radiation exposure varies as the craft passes through the trapped radiation belts and the South Atlantic Anomaly (the lower van Allen belt dips down significantly above the south Atlantic due to the magnetic pole offset of the Earth).

The significance of this inconsistency in radiation dose rate is that it allows for a device to recover from trapped charge build up to an extent determined by the recombination time in the material, the dose rate, energy and duration of exposure. Additionally, the effect of dose rate on the ELDRS phenomenon is not fully understood, and so the effect of varying very low dose rates specifically on ELDRS susceptible devices has yet to be tested. Fundamentally this could mean that a device may last longer than expected in space than the current testing regimes indicate.

Although in the current testing methods a number of devices must be tested to be assured of uniformity it has been reported that identical devices from different batches behave differently, identical devices from the same company produced in different facilities behave differently and similar devices with similar specifications from different companies can display very different tolerances to radiation exposure[CHAU-09, FLEE-94, HANS-07, KENN-09, KRIE-01, MANG-04, MESH-04, NOWL-05, NOWL-94, PEAS-91, PRIT-03, RIVA-04, TITU-99, VELO-10, WITC-96, WITC-97]. There is little that can be done in this instance as manufacturers are currently under no obligation to inform customers when their manufacturing method changes, the only way to ensure radiation testing results remain accurate is currently to repeat the tests regularly.

### 2.2 Current mainstream ELDRS testing methods

There is at present no widely accepted standard for ELDRS testing (MIL 883 1019.8 released the end of September 2010 attempts to address this by including a reference to low dose rate testing[MIL-883]), ELDRS appeared in a preliminary feasibility study for the first time in 2008 in a revision to the MIL 883 method. The ELDRS effect as described in the new MIL standard
is ‘Used to refer to a part that shows enhanced radiation induced damage at dose rates below 50 rad(Si)/s’, and for a device with no heritage information, if feasible, it would be wise to test for ELDRS, as typically in LEO the average dose rate within a craft (assuming 3-10mm aluminium shielding) is significantly less than 50rad(Si)/s (50cGy/s). The main issue with the MIL standard recommendation for ELDRS testing is that it currently requires that one test at the expected dose rate up to the expected total dose meaning this is not an accelerated test method.

As the current recommended ELDRS testing method is of the order of years in length it is unsuitable for use on COTS components as an aim of using commercial technology is to use current state-of-the art products, it is highly likely that a commercial product would have been updated during the time taken for radiation testing thus rendering it obsolete.

2.3 Research in ELDRS

In 1991 whilst investigating the gain degradation in polysilicon and crystalline emitter transistors, Enlow et al.[ENLO-91] found major differences in the radiation responses between the two transistor types when comparing degradation at different dose rates. Polysilicon emitter transistors were shown to have an increased degradation compared to crystalline emitter transistors when irradiated at low dose rates. Specifically, the gain degradation was approximately 50 times greater at 1.1 rad(SiO2)/s than at 300 rad(SiO2)/s; this was an unexpected result and one which couldn’t be simulated using high dose rate irradiation followed by high temperature annealing as used successfully in total dose testing for MOS devices as recommended in the MIL-STD 883 1019.4 radiation testing guidelines.

Since its discovery, ELDRS susceptibility has been shown in at least 30 commonly used bipolar devices and has been demonstrated in the space environment[PEAS-96, PEAS-082, PEAS-01]. Bipolar technology is found in high performance analogue to digital converters, operational amplifiers, voltage comparators and a variety of mixed signal components as either purely bipolar components in the case of bipolar junction transistors or in integrated BiCMOS components[PEAS-09]. When exposed to ionising radiation the main total dose failure mechanisms are collector-base and emitter-base leakage currents, and gain degradation; worst case scenarios for bipolar technology under irradiation at high dose rates were found to be under
reverse bias conditions across the emitter-base junction, however at low dose rates zero bias has been found to be more deleterious[FREI-98]. For the past two decades significant research has gone into the subject of enhanced low dose rate sensitivity in bipolar technology.

In 1997 the Microelectronics and Photonics Test Bed (MPTB) was launched into a highly elliptical Earth-orbit allowing it to pass through both the trapped ionising particle belt regions and regions outside the belts experienced by higher-orbiting satellites. This experiment contained a test board, designated A4, designed to measure the change in electrical parameters of devices over the course of each orbit. The results from these experiments provided evidence for ELDRS in the space environment and allowed for the direct comparison between ELDRS effects in space and radiation induced effects in the laboratory environment[TITU-98].

![MPTB Accumulated Dose](image)

**Figure 23: MPTB Accumulated Dose** [TITU-98]

Figure 23 shows the measured accumulated dose for the MPTB board. Each point represents an average dose for the 12-hour orbital period. The sudden increase in dose in the final quarter is due to high solar flare activity. The MPTB carried boards designed to test $V_{os}$, $I_{os}$ and $I_{ib}$ of linear integrated circuits, specifically the PM139Y, LM139J and LM124A.
In Figure 24 data shows the increase in input bias current with total dose comparing three ground-based tests at three constant dose rates and the space-based MPTB data. The greatest degradation is seen in the flight data, the ground data shows degradation starting at a lower total dose for the 10mrad(Si)/s rate compared to the higher constant dose rates. Figure 25 shows that later data continues to demonstrate a correlation between ground-based measurements taken at 0.001rad(Si)/s and 0.01rad(Si)/s with the MPTB data.
Results from the MPTB experiment board A4 in comparison with ground based testing did show an enhancement factor for low dose rates compared to high dose rate irradiation, however the results did not show uniformity with regards to the dose rates at which components are most sensitive. The LM124 showed greater degradation at 10mrad(Si)/s than at 1mrad(Si)/s whereas the LM139 demonstrated the opposite. For all parts tested on the MPTB board no ELDRS effect is observed above 1 rad(Si)/s however it is stated that this maximum is highly device-specific.

The MPTB experiment has confirmed that the ELDRS effect does occur in the space environment, that ELDRS can occur in a variable radiation environment since during the 12 hour orbit of the satellite carrying the MPTB it would spend approximately 1 hour passing through the Van Allan belts thus receiving a very high dose rate compared to the remainder of the orbit, and that this ELDRS-inducing variable dose rate environment can be simulated using a constant low dose rate laboratory environment in ground based testing[TURF-03].

Since the MPTB experiment the 10mrad(Si)/s dose rate has been adopted as a standard for testing devices for ELDRS sensitivity in ground based testing.

There are three categories into which current theoretical explanations of ELDRS exist, the first published mechanism was space-charge effects which would characterise ELDRS as a sup-
pression of degradation at high dose rates [FLEE-94], bi-molecular effects [TSET-05, HJAL-03] and a binary reaction-rate model [FREI-98].

Ionising radiation causes electron-hole pairs to be created in bipolar transistors, these charges interact with any present electric field and will either drift towards the complimentary charged boundary or recombine. Factors which affect this movement are the presence of charge traps either within the oxide or at the interfaces between Si and SiO2 and induced electric fields from liberated electron-hole pairs. The space-charge models address these factors by suggesting that at high dose rates slow moving holes can create an electrostatic barrier causing positive charges, holes and protons, to move in the opposite direction to normal operation; additionally the models include the trapping of holes near the interface where they can be annealed or compensated by electrons, and the trapping of holes and electrons in close proximity which creates dipoles. All of these processes lead to a reduction in trapped charge either in the oxide or at the interface which does not happen to the same degree at low dose rates, which is why the extra degradation seen at lower dose rates can instead be described as reduced degradation at high dose rates [BELY-95, BOCH-06]. Charge traps are created during the manufacturing process of transistors, the miss-match between Si-bonds and SiO2 at the interface leaves vacancies into which a charge can become trapped, additionally during the implantation phase of production crystalline defects are created which slow down the transport of holes through the structure as they become temporarily trapped in these defects. In 1994 Fleetwood et al. [FLEE-94] describe a model for explaining the ELDRS mechanism in bipolar devices following from experiments carried out on MOS devices used to simulate oxides in bipolar devices. Thermally-stimulated-current (TSC) and capacitance-voltage measurements were taken which led to the conclusion that holes could be temporarily trapped in oxygen vacancies created during dopant implantation and Si-H bonds formed during the washing and layer growth stages between implants and masks, in both the screen oxides and the Si/SiO2 interface which reduces oxide charge yield during irradiation. Following from this research, it is currently thought that at high dose rates, due to the presence of oxide traps, the velocity of holes moving towards the interface is reduced to the point where space-charge is formed within the oxide causing the measured degradation of electrical parameters since this charge impedes the normal flow of positive charge through the device; however, at low dose rates there is sufficient time for holes to move from these shallow
oxygen-vacancy traps and on to deeper traps at the interface, where they can be neutralised by electrons from the Si, before the constant influx of electron-hole pairs causes a buildup of positive charge as seen at higher dose rates [FLEE-96].

Figure 26: Space-Charge Mechanism [FLEE-94]

Figure 26 shows high dose rate irradiation (left) and low dose rate (right). At high dose rates many holes become trapped within both the oxide layer and at the interface, the temporarily trapped oxide-holes form a positive space charge which interferes with device function. At low dose rates holes become trapped near the interface where they can be passivated by electrons from the Si or annealed out over time. At both high and low dose rates electron-hole dipoles can form whereby both an electron and a hole become trapped in close proximity. It has been found that at high dose rates the number of holes compensated by trapped electrons in this manner is 11% greater than at low dose rates which leads to an enhancement factor of 2.7x in measured device degradation at low dose rates.

This model has been improved to include the effects on Si/SiO2 interface traps. It has been found that at high dose rates the release of protons via hole traps is reduced, whereas at low dose rates protons are released which migrate to dangling Si-H bonds at the interface where they can react releasing hydrogen and leaving interface traps.
Figure 27 shows the drifting of electrons ($e^-$), holes ($h^+$) and protons ($H^+$) at low and high dose rates. At low dose rates the positive holes and protons migrate towards the interface where the protons are able to interact with Si-H bonds, formed by hydrogen contamination from manufacturing and environmental contamination which forms Si-H bonds at the mismatch between the Si crystal lattice and the SiO$_2$ beneath, to form interface traps; at high dose rates positive charge barriers can form which disrupt further charge flow through the device and reverses the direction of positive charge away from the interface (depending upon bias conditions).

The second space-charge effect relates to the electric field within the semiconductor due to the presence of the created electron-hole pairs. Due to their greater effective size, holes drift slower than electrons; if due to the presence of hole traps, or a very high dose rate, there is a large buildup of holes in the semiconductor a positive charge barrier can form which effectively reverses the electric field in the region and inhibits further positive charge, protons and holes, from passing until the radiation source is removed. This leads to holes drifting towards the gate rather than the interface and thus the device no longer functions correctly [RASH-02].

Bimolecular models rely on the interaction of two particles which result in the suppression
of radiation induced degradation at high dose rates. These models are:

- Free electron, free hole recombination [HJAL-03]
- Free electron, trapped hole recombination [HJAL-03]
- Trapped electron, free hole recombination [BELY-95]
- Molecular hydrogen cracking at trapped hole [HJAL-03][ESQU-12]
- Molecular hydrogen formation (dimerisation) [HJAL-03]
- Molecular hydrogen re-trapping [HJAL-03]
- Molecular hydrogen cracking and free electron, trapped/free hole recombination [FLEE-08, HJAL-08]

All these models describe the competition of processes relating to the trapping, release and recombination of charge which occur in different proportions at high and low dose rates. At low dose rates, positive charge is able to move towards the Si/SiO2 interface and creates interface traps which leads to the degradation of the device, at high dose rates this process is either inhibited or significantly reduced due to reactions with the higher influx of more mobile electrons. Initially it was proposed that electrons could become temporarily trapped in shallow traps within the oxide before migrating and that at high dose rates a point is reached whereby the electrons have insufficient time to move from these traps and then recombine with mobile holes which have escaped initial recombination after their creation. At high dose rates the number of electron-hole pairs present in the oxide is much greater, and so there is a greater amount of recombination however the probability that an electron combines with a transporting hole is also increased which directly competes with holes interacting with dangling bonds in the oxide and interface and becoming trapped. The increased recombination at high dose rates is in itself a dose rate effect but for the purpose of finding a true dose effect at low dose rates it is the competition between trapping and recombination which is important. During the manufacturing process hydrogen contamination leads to Si-H bonds forming at the interface between the Si and oxide layers, when protons reach these points and interact with the bond molecular hydrogen is released leaving a dangling Si- bond which acts as an interface hole trap leading to device degradation.
The processes by which these protons are formed can be summarised by the following equations [HJAL-08]:

\[
\begin{align*}
\text{Eq.2.1} & \quad S_B^0 + h \rightarrow S_B^+ \\
\text{Eq.2.2} & \quad S_B^+ + H_2^0 \rightarrow S_B H^0 + H^+ \\
\text{Eq.2.3} & \quad S_B H^0 + h \rightarrow S_B H^+ \\
\text{Eq.2.4} & \quad S_B H^+ \rightarrow S_B^0 + H^+
\end{align*}
\]

Here a neutral hole trap ($S_B^0$) becomes positively charged ($S_B^+$) after capturing a hole (h), this site can then crack hydrogen ($H_2^0$) releasing a proton ($H^+$) which migrates to the interface, when this hydrogenated trap ($S_B H^0$) captures a hole it (the positive hydrogenated trap ($S_B H^+$)) can release a second proton and return to its initial state. This process occurs unimpeded at low dose rates, however at high dose rates due to the increase in electron density there is competition during the first phase of this process where an electron can neutralise the positively charged hole trap thus preventing hydrogen cracking and the subsequent proton release and interface trap formation.

All of these bi-molecular models rely on initial assumptions for the number of initial recombination centres present in the oxide, initial numbers for dangling bonds (both passivated and unpassivated), the location and distribution of the trapping sites (either oxide or interface) and the level of molecular hydrogen contamination which affects the annealing and interface-trap buildup rate. Given these assumptions, these models provide estimates of both critical total dose and critical dose rates at which the ELDRS effect will first start to be observed in a device [HJAL-03, PEAS-09]. Research in 2012 on MOS technology and gated-lateral pnp transistors has indicated that similar processes involving hydrogen cracking at defect sites may be responsible for observed low dose rate effects[ESQU-12].

The final model, binary reaction rate, was proposed by Freitag and Brown in 1998 [FREI-98]. An experiment on the LM111 comparator and LM158 operational amplifier was carried out by irradiating using an X-ray source at 50, 1, 0.3 and 0.1 rad(Si)/s dose rates and measuring the change in input bias current. It was noted that whilst both devices showed increased degradation with lower dose rates the ratio of the change in input bias at one dose rate compared to another rate to the same total dose is not constant.
Figure 28: Binary Reaction Rate vs Dose [FREI-98]

Figure 28 shows the change in input bias as a function of total dose. These results show that the rate of change/degradation of input bias current is not linear with total dose at any dose rate measured. Particularly for the 0.1 and 0.3 rad/s dose rates the rate of degradation is greatest between 0 and 150krad total dose, after which the rate of degradation decreases.

Figure 29: Binary Reaction Rate vs Time [FREI-98]

Figure 29 shows the rate of change in measured input bias current with time. Due to the short timescale the results from the high dose rate are condensed into a very small area near the
origin. All three low dose rates begin to show degradation at a similar rate and then the rate of damage decreases first from the 1 rad/s, then the 0.3 rad/s whilst the 0.1 rad/s continues to increase.

Freitag and Brown concluded from the data that the ratio of degradation at different dose rates may depend on the total dose at which the measurements are taken, that when doing multiple irradiations one cannot simply add the rates to get the correct total for the sum of the exposures and for all the measured dose rates there appears to be a time relation in that all devices showed an increase in degradation at all dose rates between 100,000s and approximately 400,000s. In order to explain these results in addition to the known causes of the ELDRS effect, namely that at low dose rates the density of interface traps increases more than at higher dose rates, Freitag and Brown posited that the buildup of interface traps could be caused by the interaction of two defects (potentially holes and hydrogen). If there is present a certain quantity of one reactant, hydrogen, which reacts with a second reactant, holes, these would form interface traps as described in the previous section. However, the rate of trap formation would change when the initial amount of hydrogen was used up and alter again when more hydrogen was released from the oxide. If this were the case one would expect to see initially a large rate of trap formation and subsequent change in measured input bias current, followed by a decrease in the rate as the hydrogen is used up and then potentially a gradual increase as more hydrogen is released; input bias degradation continues throughout these processes, it is just the rate which changes. At high dose rates hydrogen transport is hindered from reaching the interface from the bulk oxide by the mechanisms previously described, whereas at low dose rates hydrogen can reach the interface where this binary-reaction is thought to take place and form interface traps. From the model put forward in this paper, it was suggested that the transport pre-existent species (thought now to be hydrogen) to the interface is accelerated by increasing the temperature and so this could be used as a potential accelerated testing method for ELDRS. Experiments were carried out whereby a device was irradiated at both low and high dose rates and again at a high dose rate at raised temperature, the results did show an increase in degradation at raised temperature compared to room temperature however this result was inconsistent with the degradation measured at low dose rates indicating that more study was required.

Before speaking fully on current proposed accelerated testing methods, it has been noted
that in addition to the recognised contributors towards the ELDRS effect, namely hydrogen contamination during base oxide growth and oxide thickness (it is thought that a reason modern MOS devices do not show ELDRS is due to their comparatively small oxide thicknesses), there are other factors which have been shown to affect the ELDRS response of a device; device passivation, device packaging and elevated temperature tests.

Although not well understood, tests have been performed which clearly show that different types of passivation can alter or even remove the ELDRS effect from ELDRS susceptible devices. It is thought that the mechanical stress induced by the passivation on the device beneath could be the cause of this effect.

Figure 30: Passivation vs Stress [SHAN-02]

In Figure 30 the stress measured on a wafer with various passivations added is measured. A positive value is a tensile stress and negative value is a compressive stress.
Figure 31 shows the increase in input bias current in LM139s with various passivation layers. There appears to be a clear separation between those devices containing nitrides in the passivation to those that do not.

Experiments have shown that altering the passivation layer to remove nitrides can reduce or eliminate the ELDRS effect below 100krad(SiO2) total dose in tested devices, conversely one can introduce the ELDRS effect to a device by altering the passivation and introducing nitrides. Although passivation does appear to affect ELDRS susceptibility in devices, it also appears to be device specific.
Figure 32 displays the measured ELDRS enhancement factor for LM124 operational amplifiers for a number of passivation types. In this instance the p-glass/nitride passivation did not display ELDRS and the TEOS (Tetraethyl orthosilicate) variations did unlike in the LM139 experiments.

It is suggested that nitride passivations lead to radiation-softness due to them providing a source of hydrogen which migrates to the Si/SiO2 interface and interacts as described previously to cause the ELDRS effect. This is backed up by experiments which remove the passivation from devices and find that both the measured hydrogen concentration and the ELDRS effect decrease. The role of hydrogen contamination in ELDRS is further investigated through studying the effect of different packages on a device's response to irradiation. The AD590 from Analogue Devices has shown that under identical irradiation conditions a device packaged in a metal TO-52 can will degrade less than the same device packaged in a flatpack package.
Figure 33 shows the change in output current of AD590 temperature transducers at differing dose rates and two different packages. The flatpack packages appear to show significantly more degradation than the metal can packages.

The manufacturer was contacted regarding the two different packages and it was found that the flatpack devices were heat-treated at approximately 340°C. However when this was taken into account experiments still showed a significant difference in radiation response between flatpack and can device packaging. Residual Gas Analysis (RGA) showed a 0.63% H2 composition in the flatpack and an amount below the detection threshold in the metal can packaging. Further experiments were carried out on the devices with the packaging removed, and with the lids removed but taped on during irradiation. Although the devices with the lids removed and the devices with the lids removed and taped on degraded less than those still in the flatpack package, they still degraded more than those in the metal cans. It is thought that an explanation for this would be the devices were contaminated with hydrogen from the packaging, which led to the ELDRS effect observed, but after the lids are removed the hydrogen near the surface is able to diffuse out of the device, whereas deeper trapped hydrogen remains and enables the ELDRS effect to persist. Pre-irradiation Elevated Temperature Stress (PETS) testing has also been shown to affect the ELDRS response. As mentioned previously it has been noted
that increasing the temperature is thought to accelerate the motion of hydrogen through a
device which has been suggested as a method of accelerating ELDRS detection. PETS, like
passivation, has been shown to affect ELDRS response in devices but not uniformly. Devices
are typically heated to a high temperature for a short time (450ºC of the order of minutes) or
lower temperatures for longer times (125ºC for 1000 hours) and can then show either a reduced
or increased ELDRS response. One study has shown that for the LM111 after being heated
to 175ºC that the ELDRS effect is suppressed for over 10 hours. It is expected that after this
time the device would regain its susceptibility to ELDRS. The effect PETS has on ELDRS has
been suggested to be related to the elevated temperature providing sufficient energy to release
hydrogen from trap sites leaving behind metastable traps in the oxide which in turn impede hole
and proton transport to the Si/SiO2 interface, thus decreasing the number of interface traps
created during irradiation [SHAN-00]. PETS has also been strongly linked with passivation
effects as when passivation is removed PETS has no effect on the ELDRS response, it has been
suggested that stress from passivation could assist in the removal of hydrogen from trap sites
during PETS testing or that the PETS testing actually causes the redistribution of hydrogen
from the passivation (nitride based) to the oxide. Currently it is held that passivation materials
can provide a source of hydrogen contamination whilst PETS provides the energy to redistribute
the hydrogen throughout the device [SEIL-04].

In addition to standard long-term testing of components, several groups are attempting to
find an accelerated method for ELDRS testing. These methods fall into three categories, firstly,
Pre-irradiation Elevated Temperature Stress (PETS) testing whereby the devices are heated
before testing, dose rate switching where the devices are irradiated at both high and low dose
rates, and using hydrogen to induce the ELDRS effect in susceptible devices.

2.4 Switching technique for accelerated ELDRS testing

A method to estimate the ELDRS effect in devices is currently under development which uses
a dose rate switching technique. Essentially a device will be irradiated at a high dose rate and
then switched to a low dose rate, and back and forth, the shape of the curve for degradation
applying to the low dose rate irradiations is then stitched together to give an estimation of the
shape of the ELDRS response for that device.
Figure 34 is a schematic representation of the switched dose rate method whereby a low dose rate curve is constructed from many small low dose rate irradiations after higher dose rate irradiations.

Figure 35 shows experimental results for the LM139 using the switched dose rate technique.
The top image, a, shows the change in input bias current measured from low dose rate irradiations intermittently, the lower diagram, b, shows the re-constructed low dose rate curve and its agreement with complete low dose rate measurements.

As can be seen there is good agreement between the switching technique and low dose rate measurements for the devices tested, it is noted that if the dose rate curve is non-monotonic, smaller steps between low dose rate irradiations are required to avoid an underestimation in the predicted low dose rate response thus requiring initial tests to be carried out to judge whether the curve will be monotonic before the appropriate intervals between steps can be taken. The switching method has been shown to work well on all devices tested and reduces the time required for low dose rate tests, the method does require more samples of each device to be tested (a statistically significant amount for each switching step) and so for devices which are shown to exhibit non-monotonic degradation, many steps and many devices would be required and additional characterisation and testing of new devices would need to be carried out to confirm this technique [BOCH-05, PEAS-09].

2.5 Hydrogen soaking

Current research in the use of hydrogen as an accelerant points towards hydrogen bonding to dangling silicon bonds at the silicon-silicon dioxide boundaries in semiconductors; this silicon-hydrogen molecule can then be broken down during irradiation generating hydrogen molecules within the semiconductor by the following reaction: \( \text{SiH} + \text{H} \rightarrow \text{H}_2 + \text{Si} \). This hydrogen typically becomes trapped within the semiconductor acts as a charge-trapping site which then alters the electrical field present in the device [CHEN-09, CHEN-06, HJAL-03, MCLE-80, PANT-07, PANT-09, PEAS-08, RASH-04, RASH-03, SEIL-04, SHAN-04].

To test whether hydrogen is having an effect on ELDRS susceptibility experiments have been carried out in which devices are soaked in a hydrogen-rich atmosphere and then irradiated. It has been verified through these experiments that hydrogen concentration does have an effect on ELDRS susceptibility, and that this effect is proportional to hydrogen content [HUGH-09].

The method used involves de-lidding the device and placing it within a hydrogen filled atmosphere for a set amount of time to allow the hydrogen to diffuse into the device, the device is then irradiated using cobalt-60 following a method similar to the MIL 883 standard and electrical
measurements taken. The hydrogen atmosphere is varied from 0.5% up to 100% in steps and it was found that the device under test degraded faster under irradiation after the 100% hydrogen soaking as opposed to the lower percentage hydrogen atmospheres [Hugh-09].

This method has demonstrated that hydrogen has an effect on ELDRS however it introduces a number of complications. The primary complication is that the method requires the semiconductors to be fully exposed, de-lidded. This process requires either chemical or laser etching of the device to expose the unprotected semiconductor beneath. The process is by nature damaging and from a feasibility perspective for wide-scale testing it is time consuming and risks damaging the device. In addition the experiment shows that hydrogen can diffuse out as well as in to a device and so the hydrogen concentration within the device at any given time is an approximation. There is no control where the hydrogen is within the semiconductor. As mentioned at the beginning of this section it is thought that the key location for hydrogen to have a deleterious effect on devices is at the boundaries between the silicon and the oxide layers since this is where hydrogen by means of water is introduced during the manufacturing stage of a device [Rash-03, PANT-09, MCLE-80, Flee-94], thus to introduce hydrogen throughout the device is to create an unrepresentative test environment. However, as an experiment to show that hydrogen affects ELDRS susceptibility the results are clear [Peas-10].

Since the experiments described in this thesis, research in ELDRS has continued to fall broadly into three categories, testing components whilst altering the testing environment, developing further simulations to develop theoretical models, and testing new accelerated ELDRS methodologies. In addition to these, papers are still produced whereby devices have been tested according to the unmodified MIL-STD-883 ionising radiation testing method at low dose rates in a non-accelerated fashion to produce results for ELDRS susceptibility [Mare-13, Mare-14, KRUC-14, TOSC-13]. Review summary papers have also been produced which provide a historical perspective on ELDRS and low dose rate effects [Flee-13]. In terms of testing components, new generation SiGe technologies are being tested and have been found not to display dose-rate effects when performing irradiations at high and low dose rates and comparing the degradation [Flee-14]. Experiments involving the lowering of the ambient temperature to < 125K [ADEL-12], and others where the biasing conditions of the devices under test were changed have both demonstrated these variables can affect the response of a device to low dose rate
irradiations[KRUC-11]. Whilst it is already known that temperature during annealing can affect the response of a device this research could be used to give a better indication of the ELDRS response of a device in the space environment for devices which are to be used at temperatures much lower than the current room-temperature tests which are performed according to the MIL standard. Radiation tests at very low dose rates have confirmed that different technologies display the ELDRS effect at different dose rates and that there is thus far no uniformly lower-bound to the dose rate at which ELDRS effects take place[CHEN-11]. This research also demonstrated that some ELDRS-free devices became susceptible to ELDRS at dose rates much lower than those currently used in ELDRS testing. With regards to simulations, research continues in attempting to predict the ELDRS effect using charge-trapping models[ZEBR-13, ZEBR-14, ESQU-11]. Whilst useful in potentially explaining the cause of ELDRS, the majority of the research is not used to develop an accelerated method for testing devices, but can be used to predict whether a device may be susceptible given sufficient data on the composition of the device. Simulations based on hydrogen contamination continue to indicate the key role of hydrogen in ELDRS susceptibility, research has focussed on finding the mechanism by which hydrogen interferes with the operation of a device when under irradiation, it has been put forward that whilst always involved, the dominant process by which the hydrogen engages with traps in a device varies depending upon concentration. Research into the mechanisms by which hydrogen cracks and bonds in a substrate continues[ESQU-12, ROWS-12]. In terms of accelerated methods, the switched dose rate method is still in use and being further developed, one group have suggested performing switched temperature testing in a similar fashion and shows promise in competing with the switched dose rate method. Neither of the accelerated methods proposed have been uniformly adopted by the testing standards as of April 2015, and whilst the switched-dose rate method has been used successfully, it remains limited to devices where the response of a device to radiation is known and in order to reproduce an accurate low dose rate response many devices need to be sacrificed which may make this method unappealing to organisations wishing to test a proprietary device where the quantities available for testing are limited[ZHEN-13, BOCH-11, GONZ-11, ?].
2.6 Current trends in spacecraft COTS technology

It is important to study the trends in COTS technology used in the space industry when developing a test regime as to avoid testing for effects which only apply to technology which is being replaced or obsolete, as such a brief analysis of current trends has been completed.

Figure 36: Trends in device family testing from 2003 - 2009 at JPL test facility

Figure 37: Comparison between numbers of devices tested and numbers exhibiting HDR/LDR discrimination and ELDRS

Figures 36 and 37 show the results of total dose tests carried out at the JPL test facility
between 2003 and 2009 [RIVA-04, PRIT-03, KENN-09]. The bottom axis show the device families and the vertical axis is the number of devices in each family tested. There has been a definite trend towards further bipolar device testing and to a limited extent CMOS (Complementary Metal–Oxide–Semiconductor) devices. It should be pointed out however that this may be commercially or project driven and so may not be representative for the entire space industry.

Of the devices tested Figure 37 shows the number in each category followed by the number of those which exhibit a difference in electrical response when under low dose irradiation to high dose irradiation, in addition the green bars represent the number in each category which then showed a confirmed ELDRS effect. (Devices may show increased degradation at higher dose rates in a non-linear fashion and so show LDR/HDR (Low/High Dose Rate) discrimination but not ELDRS).

Current COTS technology appears to follow a trend of becoming physically smaller, and as it does so more complicated as newer, smaller devices need to carry out the same function of their larger predecessors. In terms of radiation effects this means that single event effects become more important as a single event on a smaller, more complicated device has a greater effect than on a simpler, larger one. Total ionising dose effects still remain a constant concern, including the ELDRS effect, as space missions become longer and the monetary cost of failure becomes greater. Bipolar devices are seen to be susceptible to ELDRS, current trends indicate that there is a move to using MOS (Metal Oxide Semiconductor) devices, however there are still bipolar devices which remain irreplaceable. In terms of MOS devices the trend is for the thickness of the oxide to become smaller, this may explain why MOS devices currently appear to be ELDRS free, as although they are composed of the same material as bi-polar devices, the oxide thickness is typically much smaller and only majority charge carriers are used (bi-polar devices as the name suggests use both majority and minority charge carriers).

2.7 Conclusions from the literature review

The review of the current research in the area of total ionising dose testing has revealed a number of key points. All the major testing regimes are very similar, differing only slightly on the procedure. The smaller test regimes used by other space organisations tend to be heavily based upon the MIL 883/ESA routine. These test regimes all use cobalt-60 as their primary
source of ionising radiation and all irradiate at high dose rates and then anneal at increased
temperatures to simulate semiconductor ageing.

The current research in the field of ELDRS can be split into two sections, firstly, research
into the physical processes involved in the ELDRS effect, and secondly empirical low dose rate
testing to build up a catalogue of devices known to be susceptible to ELDRS.

The physical process involved in the ELDRS effect is not fully understood however it is
thought to be caused by the properties of the charge carriers within the semiconductor. Ionising
radiation causes the formation of electron-hole pairs within the material. Holes are in fact the
local absence of valence electrons after an electron has been ejected due to the incident radiation.
When under the influence of the electric field present in the active semiconductor the positive ion
will be attracted to the negative terminal of the semiconductor, and the electron to the positive
terminal, due to this difference in size the positive ion will move at a much slower velocity. As
a consequence of this it will take longer for the positive ion to be neutralised than the faster
moving electron, leading to a build up of positive charge when under constant irradiation. In add-
tion to this the electrons and holes can become trapped within the semiconductor layers, again
due to size and charge differences the rates at which electrons and holes become trapped and
‘de-trapped’ are different. The functions of a semiconductor device rely on the control of charge
through the device and this is done by having control over the electric fields within the device by
varying the applied potential difference to the relevant terminals. When charge builds up within a
semiconductor due to trapped charge or the slow moving holes the electrical characteristics of the
device change as the presence of additional electric fields caused by the built-up charge interferes
with the nominal movement of charge through the device due to the applied operating potential.
This change in electrical characteristics manifests itself in a change in measured electrical para-

ters of the device [BELY-95, BOCH-06, BOES-90, CHAV-05, CHEN-07, CHEN-81, FLEE-94,
FREI-98, GRUB-98, HAYA-07, KRUC-08, KRUC-09, MINS-04, RASH-02, ZEBR-05, ZEBR-06].

It is currently unknown whether there are threshold levels to the ELDRS effect though there
is active research in this area which seeks to apply a theoretical lower threshold at which the
ELDRS effect would take place. An important area of research is the effect of hydrogen on
ELDRS susceptibility. It has become accepted that the presence of hydrogen within a semicon-
ductor affects the devices susceptibility to ELDRS. Hydrogen is introduced during the manufacturing process of the silicon wafers as water is used to clean the layers which make up the semiconductor after they are deposited and etched. There is a section of the MIL 883 standard which aims to test for water and moisture content of devices before the radiation testing phase of the standard is reached, though it does not test for hydrogen [TSET-05, TSET-07, TSET-07, TSET-10, ZEBR-09, HUGH-09, PEAS-09].

ELDRS has been recognised as an emerging threat as it has recently appeared as a preliminary addition to the MIL 883 standard, and in the latest edition (released September 2010) has become a full section of total dose testing. At the time of writing there are only two methods which have been accepted for use in ELDRS testing, the first is from the MIL 883 1019.8 standard, however this is not an accelerated test, it is a lifetime test at the expected dose rate. The second, is the switching dose method [BOCH-05], is put forward as an accelerated method. The method involves a series of steps from high dose rates to low dose rates and reconstructing the low dose rate curve from ever increasing levels of initial radiation induced damage. Whilst accepted, it suffers from requiring a large quantity of test components since at each dose rate switch a statistically significant number of devices are required, and the number of switches correlates to the precision of the reconstructed low dose rate curve making it desirable to have the highest number of switches possible, this process becomes more cumbersome and potentially prohibitively expensive when the low dose rate response is non-linear and a high degree of precision is required. The advantages of this method are that it requires no modification to the device and makes use of the same facilities as current MIL 1019.8 radiation testing, for verification however it still requires low dose rate tests to be conducted.

The basic physical principles behind the ELDRS effect are being researched and it has been found that hydrogen content has a direct effect on the dose rate at which ELDRS presents in a susceptible device. It has been found so far that bipolar technology is susceptible to ELDRS and whilst there is a general trend to use MOS devices instead, there are a number of key device families (figure 36) which cannot be replaced and so need to be tested for ELDRS susceptibility.
3 Experimental Theory

The literature review has shown that ELDRS is an emerging threat as recognised by the MIL standard and the research indicates that there is a need for further understanding into ELDRS susceptibility. Hydrogen content has been shown to have a major effect on ELDRS susceptibility and is an unavoidable consequence of the current semiconductor manufacturing methods. Hydrogen soaking has shown to increase the ELDRS effect in devices however the current method requires de-lidding the device causing inherent damage.

It is therefore proposed that one uses an ion beam to for the first time directly implant hydrogen within a semiconductor device to probe the ELDRS effect. A hydrogen beam can be focused to implant hydrogen at different points within a device to probe the effect for the first time rather than introducing hydrogen throughout the device as per soaking. This method will allow the study of the effect of hydrogen at the boundaries within a semiconductor which is not currently possible using any methods proposed in current research. Hydrogen implantation will enable the location of manufacturer-introduced hydrogen vulnerability points within a device with the aim of developing a model for the electrical behaviour of devices which have hydrogen introduced at different points when under irradiation. Using the information gathered from hydrogen implantation experiments there is the hope of developing an accelerated ELDRS testing method using implantation by having better understood the processes involved between hydrogen and semiconductor sites under low dose rate irradiation.

Devices should be selected which meet the following criteria: They are used in the space industry, since this is the focus industry for this thesis; they are based on bipolar technology since this is the group which is most susceptible to ELDRS and currently the MIL 883 1019.6 standard recommends that all bipolar technology which has not yet been tested, if to be used in a low dose rate environment, should be tested for ELDRS at low dose rates; should have sufficient literature available regarding the response to radiation to make an informed comparison with published data; should be known to be ELDRS susceptible; and a control which is thought to be ELDRS-free.

The devices when under irradiation should be in conditions which closely match the environment in which they will be used for purpose, the temperature should not fluctuate outside

71
of the manufacturers specifications and the devices should be kept at room temperature at all times to avoid annealing effects which would compromise the reliability of the results. Testing the devices in this manner also allows for the future comparison between these ground based tests and space applications where the device is actually in use and does not have its electrical parameters being measured constantly. In order to be statistically relevant, at least four devices of each type should be tested and all measurements repeated.

Since the outcome of this research is a proposal for a new method of accelerated ELDRS testing, the resulting method should be compared with the current prominent accelerated method, the switching dose rate methodology, although the ion implantation method is closer to the previously proposed hydrogen soaking method, only the switching dose method is currently in use since the hydrogen soaking method only confirmed that hydrogen was responsible for the ELDRS effect and induced the effect in all devices tested it was unable to identify devices which would be ELDRS sensitive before hydrogen soaking.
3.1 Device Selection

Two devices have been selected for study, the AD590KF temperature transducer from Analog Devices, and the LM124 operational amplifier from National Semiconductor. These devices have been chosen due to their wide use on spacecraft, their similarities in passivation technology, the availability of research for suitable comparison and their susceptibility to ELDRS, additionally an ELDRS-free version of the LM124 will be used as a control and for comparison to the hydrogen soaking experiments[PEAS-10].

The AD590 selected is a 2 lead flatpack component which acts as a current source outputting $1 \mu A/K$. It’s operational between -55$^\circ$C to 150$^\circ$C and calibrated by the manufacturer under a 5V power supply at room temperature. In spacecraft the AD590 is used to monitor the temperature surrounding components.

The AD590 operates by comparing the base-emitter voltages of two identical Silicon transistors which operate at a constant ratio of collector current densities. The difference in the base-emitter voltages only depends upon the temperature and so this is known as a PTAT (Proportional To Absolute Temperature) voltage device.
Figure 38 shows the schematic circuit layout of the AD590, the transistors labelled Q8 and Q11 are responsible for the PTAT voltage whilst Q10 supplies all the bias and substrate leakage current to the circuit thus keeping the output current PTAT.
Figure 39 shows a micrograph of the inside of the AD590 and highlights the position of the transistors visible from the surface.
Figure 40 shows the dimensions and metallisation of the AD590 (Analog Devices Data sheet).

Given the predicted spread of an ion beam, and that this spread increases proportionally to the number of layers the beam must traverse, it is preferable to select a target site which is isolated from areas which would prevent the results being interpreted, for example, targeting the top of the device would implant transistors 1-4 and possibly Q5 and Q6 which cannot be seen. It is also necessary to select a target which limits the amount of metallisation traversed, Q11 appears to be the best target site as it is less covered by metallisation than the more isolated Q9, and also is one of the two transistors used in creating the PTAT voltage thus constituting a sensitive area to the functioning of the device.

The AD590KF is bonded to a ceramic back and covered with a gold lid, due to the delicate nature of the device it is not feasible to remove the device from the ceramic without damaging the device. Simulations were done to assess the possibility of implanting through the lid or whether this needs to be removed.

The LM124 is a quad operational amplifier and is widely used in this function in the space environment, it too is tested at 5V and each internal amplifier is internally compensated and runs independently from a single supply voltage.

Figure 41: LM124 Schematic
Figure 41 shows the internal layout of the 4 amplifiers inside a single package.

![LM124 Circuit](image)

Figure 42: LM124 Circuit (1/4 LM124)

Figure 42 shows the circuit for one of the four amplifiers inside the LM124 package.

![Microscope Image](image)

Figure 43: Microscope image of LM124

Figure 43 shows a microscope image of the surface of the LM124 after mechanically removing the ceramic lid. Visually, features cannot be identified for suitable target sites at this level, it is possible that the passivation used on the surface is hindering inspection.
Figure 44: Metallisation photomicrograph of LM124 (section inset)[SEIL-04]

Figure 44 shows a clearer image of the surface of the LM124, this was taken directly from the die which explains the improved clarity. The most exposed areas, being the ones most suitable for implantation, appear to be at the edges next to the bond wires, or in the centre surrounding the power and ground connections. The outer edges do not appear to represent a recognisable part of the circuit and so would not make a good choice for target sites.

The SRIM simulations gave an indication of the spread of the implanted ions, and this spread can be predicted however as a safety margin it was unwise to have implants within 5 microns of each other since the simulations have shown that whilst most ions have a tendency to stay within a confined region, there are inevitably some which are less confined. To avoid over-dosing the central power distribution region of the LM124 it was decided that each quadrant would be implanted as shown in figure 44.

As a test to verify whether the implanted ions are spreading from the target or damaging unintended areas, a test device will be implanted but only in 3 of the four quadrants. If the
remaining quadrant is still functioning after implantation it will confirm that either the ions did not spread into that region or that they did not spread into the power distribution region (which would cause a change in operating parameters).
3.2 Hydrogen Implantation of Devices

3.2.1 Theory of hydrogen implantation

Modern semiconductor devices consist of a complicated arrangement of metal, silicon, insulator and oxide layers as shown in the scanning electron micrograph in figure 45, hydrogen would need to be implanted at or near to the boundaries between these layers in order to simulate the hydrogen introduced during the manufacturing process.

![SEM micrograph of semiconductor device structure.](YORK-10)

The implantation process itself would take place at an ion beam facility whereby hydrogen ions would be accelerated and targeted at the selected test device. The ions would pass through the device depositing energy until there is insufficient energy to pass further. The ions would be targeted at the boundaries between the silicon and silicon dioxide where (unless annealed out) they will remain once a sufficient concentration has been reached or if they become bonded to dangling bonds present at the silicon/silicon dioxide interface.

This PhD has discussed in section 2.5 the current application of hydrogen soaking to study the effect of ELDRS in bipolar devices and that the experiments have shown positive results for a relationship between hydrogen and ELDRS. The following simulations were used to show the feasibility of introducing hydrogen into a device through the packaging using a hydrogen ion implanter.

The software package used for these simulations is called SRIM ([www.srim.org](http://www.srim.org)) which is a
software tool used to simulate ion beam transmission, ion implantation and ion range in selected targets. The software has been used here to find the energy required to implant hydrogen into a simple model of a semiconductor and to approximate lateral spread of the beam within the target. The thicknesses used for the layers are typical for modern devices and the purpose of these simulations is to determine an approximation of the energy required to implant hydrogen into a real semiconductor to test for feasibility. The simulations show an energy of 210keV is required which is well within the limits available at the Ion Beam Centre facility at the University of Surrey.

Figure 46: SRIM plot for H ion deposition depth in semiconductor layers at 210 keV
The simulations in figures 46 and 47 show the ion tracks through the programmed materials and also reveal the spread and accuracy of ion deposition, the lateral spread from the centre of the beam is approximately 3 microns and the depth can be altered by varying the acceleration potential. This method thus allows the implantation of hydrogen into typical semiconductor thicknesses used today within the energy range possible at the facility on site. The deposition region is controllable within lateral error and the concentration and depth can be controlled. Preliminary experiments would have to take place in order to match the approximations made by the SRIM simulations to the real-world capabilities of the ion implanter at the Ion Beam Centre.

Whilst the simulations showed that ions could be implanted through a sample package material, the spread of the ion tracks both laterally and in terms of depth is greatly improved with the removal of the package lids, subsequently due to the reduction in material the energy required for the implants could be reduced which reduces the physical damage to the device from the implantation.

In addition to the SRIM simulations to determine implant energy, sacrificial samples for each
device were used. These devices were placed into the same ion beam which was later used for the actual experiments and implanted at increasing acceleration potentials until the correct depth was reached. This depth is the point at which the recorded back-scatter spectra reflected the expected elements within the target location, if the signal indicated the implant was mostly in Aluminium, which is used to shield the device, the depth was incorrect, if the spectra gave a strong signal for Silicon/ Silicon oxide and we were able to covert this data into an image which matched the expected construction of the device at the target depth then these implantation conditions were recorded and subsequently used in the experiments.

3.2.2 Aims and requirements of hydrogen implantation experiment

The aims for the hydrogen implantation experiment are to successfully implant hydrogen into the device in a specific region known to be susceptible to hydrogen contamination which was gathered from the literature review, for the hydrogen to be implanted in a manner which is quantitative, for the implanted hydrogen to be contained within the target area without spreading and for the devices to be functional after implantation in order for useful measurements to be made during irradiation.

The quantitative nature of this experiment relates to knowing how much hydrogen has been introduced into the device, Section 2.5 of this thesis describes the hydrogen soaking experiments whereby molecular hydrogen was allowed to passively diffuse into a device from a selection of atmospheric concentrations, following from this the device and the atmosphere would reach an equilibrium state, however the amount of hydrogen introduced into the device was not discussed and this research used the value for the molecular hydrogen concentration in the atmosphere as opposed to present in the device post-exposure. Due to the nature of hydrogen implantation by an ion beam, the location of the hydrogen can be actively targeted as opposed to passive diffusion, and the number of ions implanted can be controlled which gives a quantifiable aspect for the amount of hydrogen introduced into the device which is not present in the hydrogen soaking experiments.

• 1. De-lid sample device from each set to be tested for depth profile to select target depth and ion beam energy: In order for the devices to be implanted with hydrogen and for
that hydrogen to be confined to the smallest possible area the lid of the device must be removed to reduce both the amount of scattering and the energy required for implantation. A sacrificial sample of each device is taken to verify that the predicted implant energy is appropriate and measure the depth at which the implantation will occur.

• 2. The devices are all to be electrically characterised before implantation and the response to radiation measured for comparison after implantation: The devices must perform their function after the implantation, and in order for the electrical degradation to be measured after both irradiation and implantation, baseline data must be taken as to the device performance before and after implantation.

• 4. The devices should all be implanted with hydrogen in the same environmental conditions: The literature has reported that hydrogen contamination from the atmosphere is possible, that temperature and storage can affect device performance as can physical stress, as such, the devices should as much as possible be kept in an identical environment throughout the implantation and subsequent experiments.

• 5. After implantation the presence of hydrogen at the target site should be verified: It is important that the implanted hydrogen not spread throughout the device or escape the device completely, preliminary implants should be performed to ensure the energy, flux and implant time are at appropriate levels to ensure the implanted hydrogen is stable at the target locations.

3.2.3 Experimental design

It is important to confirm after implantation that the hydrogen remains in the designated region and to have a statistically significant number of devices survive the process for testing, 3 devices minimum, 4 preferable, as such 20 AD590 and 64 LM124 (LM124 to be split between implant doses) were prepared for implantation. Hydrogen does diffuse in silicon and this process is well understood, at room temperature low concentrations of hydrogen will diffuse through silicon at $10^{-10} \text{cm}^2\text{s}^{-1}$ and follows a temperature dependence, however this rate of diffusion is slowed down significantly when the hydrogen interacts with defects or Si/SiO2 boundaries where it can become trapped[PEAR-91][HALL-91]. It has been found that a concentration of greater than 84
$10^{15}$ H ions/cm$^2$ in silicon renders them immobile under annealing up to 510K [FINK-95], so the target concentration for the implanted hydrogen should be greater than $10^{15}$ H ions/cm$^2$.

### 3.2.4 Predictions

The hydrogen-soaking experiments indicate that the greater the concentration of hydrogen the greater the susceptibility of ELDRS, the same result is expected here in the ELDRS susceptible device. A change in the characteristics of the device thought to be susceptible is also expected but as the threshold ELDRS dose rate for each device is unknown it cannot be predicted to what extent the ELDRS effect will manifest at the dose rates used in the irradiation experiment. The theory suggests that the presence of hydrogen within the device will have the greatest effect on ELDRS at the oxide boundaries.

### 3.2.5 Conclusions

This method for direct hydrogen implantation as opposed to conventional soaking methods allows for more precise control over the concentration and location of hydrogen within the device. Consequently this method allows devices to be probed by implanting hydrogen at different locations within the devices to see which locations have the greatest effect on ELDRS susceptibility. Finally, the data gathered from the implantation experiments after irradiation will allow for direct comparison between devices and hydrogen location.
4 Experimental Methods

4.1 Implant Simulations

SRIM was used to simulate the implantation of Hydrogen ions (protons) into the AD590KF and the LM124. The packaging and passivation details were acquired through data sheets and lists of materials used during manufacture and previous research, by means of this data an approximation for the passivation material and packaging thicknesses can be made which are suitable for the purpose of simulations. SRIM can be used to show the depth and spread of implanted ions into planar layers of material where both the composition of the target and the ion energy can be specified. This enables implantation trials to be conducted and the correct energy selected before any actual implants take place. The simulations use approximate data, inferred from device dimensions, the materials present in the packaging, passivation data and references made in published research whereby COTS devices have been dismantled, the purpose of the simulations was to provide a guide for the implant energies used for the sacrificial samples which were then used to find the conditions required for the actual experimental implants.

Figure 48: Implantation simulation of H into AD590 with Gold lid at 500keV [SRIM]

Figure 48 shows that the initial selection of 500keV for implantation energy into the AD590 is insufficient, the gold cover completely stops any of the ions from penetrating into the device. Raising the acceleration energy will increase the depth of the implants but will also increase
the recoil energy when the H ions interact with nuclei which will cause a greater amount of displacement damage.

Figure 49: Simulation of H range in AD590 through Gold lid at 1.8MeV [SRIM]

Figure 49 shows the range of ions at 1.8MeV into the AD590 through the Gold lid. It would appear that the implantation at this level is successful since the majority of the ions reached the Silicon region of the device through both the Gold and the passivation layers. The energy could be reduced so that the peak number of ions implanted were closer to the boundary between the oxide and the silicon.
Figure 50: Implantation simulation of H into AD590 with Gold lid at 1.8MeV [SRIM]

Figure 50 shows that at this energy the implanted H ions are not focused, and whilst they do reach their target depth the amount of spread caused by interactions in the Gold lid causes a loss in resolution.
Figure 51: Implantation simulation of H into AD590 with Gold lid at 1.8MeV, transverse view [SRIM]

Figure 51 confirms the spread of ions, almost 17 microns at worst case with a primary focus of approximately 4 microns around the centre. Whilst 4 microns is an acceptable beam width, the amount of spread of ions through the rest of the device is unacceptable.

Figure 52: Simulation of Damage Events from implanting H into AD590 at 1.8MeV [SRIM]

Figure 52 shows the displacements as a function of depth through the device when implanted
at 1.8MeV, as can be seen a lot of damage occurs. Whilst high temperature annealing may repair some of these events, it may also cause the spread of the implanted hydrogen away from the target site thus lowering the total effective targeting resolution.

The lid from the AD590KF can be removed mechanically without damaging the device. The Gold is used to conduct heat to the rest of the package into which the actual circuitry is embedded. The following simulations will assess the implantation of Hydrogen into a delidded AD590.

Figure 53: Simulated H Ion range in AD590 and LM124 at 600keV [SRIM]

Figure 53 shows the range of ions at 600keV into the devices. The AD590 and the LM124 are passivated by the same compounds (unless specified otherwise during ordering), thus these simulations are useful for predicting the range and effects of ions implanted into both devices. 600keV is an appropriate energy in terms of range for both devices.
Figure 54: Simulated H Ion lateral dispersion in AD590 and LM124 at 600keV [SRIM]

Figure 54 compared to the same transverse view for the AD590 with the Gold lid shows very little spread of ions through the device, highlighting the scattering effect of the Gold layer. The approximate spread is now 2 microns in diameter.

Figure 55: Simulated Displacement events for H implantation into AD590 and LM124 at 600keV [SRIM]

Figure 55 shows the displacement events at 600keV into both devices, whilst the number of displacements appear to increase this is affected by the amount of time the implants run for,
which in turn is affected by the beam current. The greater the beam current the more ions are implanted per unit time and so the less time the implantation runs for. In these simulations the beam is allowed to run until accurate data can be measured for the depth and spread of the ions at each energy. The number of displacements per ion at 600keV is 19 whilst at 1.8MeV there are on average 30 displacements per ion since the greater energy allows for further recoil events.

Figure 56: Simulated Distribution of H ions in AD590 and LM124 at 600keV [SRIM]

Figure 56 shows the simulated distribution of implanted Hydrogen in both devices taking data from the previous implantation figures, the spread through the crystal can be seen to be focussed with minimal spread to adjacent areas.

4.1.1 Implant procedure

Prior to implantation, the devices need to be secured to the stage to be inserted into the vacuum chamber at the end of the beam line. In order to avoid unnecessary charging the devices need to be fully grounded. A prototyping board was cut to match the width of the stage and IC holders were soldered into place. The soldered joints were checked for conduction with a multimeter before the components were inserted. The components then had their temporary lids removed and were inserted in groups of 5 into the holder leaving a space between each to ensure safe removal and also so that a known distance would be between each sample.
The samples were then numbered and photographed, as seen in Figure 57. Screw holes were drilled into the lower end of the board so that it could be fixed into position and clamped at the top using a further screw and stiff wire. To the left of the board the calibration samples on the stage can be seen. These were used to focus the beam and set the co-ordinate origin from which each of the target implant locations could be assigned.

The AD590s were secured using a combination of clamps, tape and cut metal plates. First a single plate of aluminium was cut to fit the stage, this was wrapped with two layers of conductive tape and secured to the stage. To this, using tweezers, the AD590s were placed. The legs on the devices needed to be straightened before placement and the ceramic head of the device pressed into the conductive tape without damaging the exposed device interior.
Figure 58: Placement of AD590 into holder for ion implantation

Figure 58 shows the placement of the AD590s. A second piece of aluminium was cut to two thirds the width of the previous and had one side covered in the conductive tape, this was placed, tape-side down, onto the legs of the devices to secure them in place. Due to the legs coming from the middle of the device rather than being flush with the back of the package the tops of the devices were bent forwards at an angle, these then had to be pushed back down to enable them to be orthogonal to the beam once placed in the vacuum chamber. A line of copper clamps was then used to firmly secure the mounted devices to the stage to avoid slippage once inserted vertically into the chamber. A multimeter and probes were used along the exposed legs of the devices to verify a conductive path to the stage for the purpose of grounding.
Figure 59: Loading of devices into ion beam chamber

Figure 59 shows the devices being loaded into the end vacuum chamber of the ion beam. The stage needs to be inserted by hand into the vacuum chamber whilst checking the alignment using a porthole on the side. The stage needs to be aligned such that the devices to be implanted are facing the beam and that there is sufficient room above and below the sample holder for the stage to move up and down when selecting targets without impacting the chamber walls as this would causes the motor to skip positions and render the origin calibrations useless.
Figure 60: LM124 inside vacuum chamber in preparation for ion implantation

Figure 60 shows the devices within the vacuum chamber. A light is shone inside the chamber whilst the stage is being aligned to permit visual inspection and the use of the optical microscope which is used to locate the target sites on the devices prior to implantation.

Figure 61: LM124 under targeting microscope in ion beam end chamber
Figure 62: Target area of LM124 under optical microscope in ion beam end chamber

Figure 63: AD590 under targeting microscope in ion beam end chamber
Figures 61-64 show the devices viewed through the optical microscope in the ion beam end vacuum chamber. The focus is off-centre as the devices are aligned to be orthogonal to the incoming ion beam not the microscope. The microscope is used to manually align where the beam will hit. The stage is moved to one of the standard samples is lined up with the incoming beam aperture and the microscope. The beam is allowed to pass through so that it’s position can be seen and the microscope can be adjusted so that the beam position will be known relative to the focus of the scope. The beam is terminated and the stage is moved manually to align a target mesh using the microscope as a guide. Once the target has been centred, the light is turned off and the beam is activated and a backscatter image of the target is formed to check whether the optical alignment matches the ion beam alignment. Once any necessary changes are made to the focus the beam is terminated and the stage is moved via computer control to the first target site. Ideally each target site can be pre-programmed into the computer by manually locating and selecting sites using the calibrated optical microscope, the computer will then activate the beam, raster across a site, deactivate and move on to the next site without
human intervention. It was found that for the longer implants, at the highest dose rates the calibration was not always sufficient, as such these implants were done by manually targeting sites.

For each component, a sacrificial sample was selected which would be implanted to gauge the effectiveness of the beam at this energy by profiling depth through the device. This also afforded the opportunity to collect PIXE (particle induced X-ray emission) spectra which allowed for the composition of the devices to be analysed.

Figure 65: PIXE spectra for LM124

Figure 66: PIXE spectra for AD590

Figures 65 and 66 show the PIXE spectra for the components. The signals for both Silicon and Aluminium are high as to be expected but there are also other elements present which are used in the interstitial layers of the device as mentioned during the section on device fabrication.
The Gold in the AD590 is suspected to be what remains of the lid (which will be confirmed later with particle maps), the Tungsten is used as plugs in the internal electrical connections between transistors. The Tin, Lead and Silver would also be present to form internal connections between layers in the devices.

These spectra can be mapped so that we can see where on the device these X-ray emissions are occurring, and hence where each element is present.

Figure 67: PIXE map for LM124

This map in Figure 67 shows the location of Silicon, Aluminium, Silver and Lead signals being detected. As expected Silicon is present throughout the device, the bright green areas indicating where there is less Aluminium blocking the signal and the dark areas around the
edges are where the Aluminium in the bond wires are completely blocking the Silicon signal from beneath. The Aluminium signal shows the Aluminium mask and the dark areas are where the ions will penetrate deeper into the device since they are not being blocked by the Aluminium. The Silver signal appears to be coming from beneath the die and the bond wires (due to the presence of a bond wire 'shadow'). It is suspected that this signal is from the Silver infused epoxy used to attach the die to the packaging after fabrication. Similarly the lead signal shows a scattered presence within the device with the majority around the edges where solder is exposed from the base of the packaging.
Figure 68: PIXE map for target area of LM124

Figure 68 shows the Aluminium map for the LM124, the darker the area the more penetration into the Silicon beneath. This map was taken from one LM124 during implantation and shows all four quadrants on this chip. The beam was manually aimed to the rounded feature in the centre of each quadrant and then raster scanned across a 250x250 micron area.
Figure 69 shows the PIXE maps of the AD590. Silicon is present throughout, a strong signal (red) coming from around the target area, the blue area to the right indicates a heavily shielded area towards the top of the device, possibly where the second PTAT transistor is located. The Aluminium signal is almost the inverse of the Silicon signal, the very bright area towards the left of the image is one of the pads for one of the two bond wires. Both Nickel and Gold are present at the edge showing where the Gold lid has been removed, there is also a strong Gold and Tin signal coming from beneath the device, possibly indicating a thermal mounting or adhesive used to bond the device to the back of the ceramic packaging. The presence of Chromium indicates
its possible use in the back packaging of the device, although there is a weak signal coming from beneath the shielded area on the right (top) of the device.

Figure 70: PIXE map of target area in AD590

Figure 70 shows the map of the target area for the AD590, the Aluminium signal is on the left and the Silicon on the right. Both the Silicon and Aluminium maps are shown and are the inverse of one another as one would expect if the Aluminium is shielding the Silicon. Here the beam was scanned over a 400x400 micron area.
4.2 Long term total dose irradiation experiment

The only definitive way to test for ELDRS is by irradiating at a low dose rate, in the mGy region for dose rate. The purpose in performing a test at this dose rate is to compare the rate of degradation with the high dose rate tests, both on the implanted and unimplanted devices. For the data from the low dose rate irradiations to be useful, the irradiations need to continue to a total dose of the same order as the high dose rate tests, whilst the high dose rate tests take a day to perform the low dose rate tests require over 4 months to reach a comparable total dose.

4.2.1 Experimental design

The long term experiment is required as a control to the accelerated tests typically performed by the MIL 883 standard and will be following the method suggested by this regime for ELDRS testing.

Cobalt-60 was the source used up to the maximum limit allowed on the premises which is 555MBq, this gave a usable dose radius of approximately 10cm around the source(s) (the precise required distance from the source was calculated from taking measurements once the source is in place). Cobalt-60 was used as this will allow results from these experiments to be compared with measurements from published data from facilities basing their tests on the MIL 883 regime.

The data will be gathered continuously from each device using data logging equipment so that changes can be noted as they happen and a period of 4 months will be set as sufficient time for the total dose to accumulate to a degree at which the known ELDRS susceptible devices are known to fail. These results can then be compared to accelerated tests conducted at the National Physical Laboratory (NPL).

4.2.2 Health and Safety considerations

When using ionising radiation health and safety is a priority, as such the following constraints have been taken into account. Firstly the experiment itself will be surrounded by lead bricks to a thickness of 20cm above and around the sides (the distance between the source and the room below is sufficiently large for the dose rate to have decreased to safe levels). In addition the entire experiment will be kept in a sealed and locked room where there is no unauthorised
or unnecessary access by staff or students. The experiment is designed so that the shielding and test boards can be in place before the source is present which can be dropped into place just before results begin to be taken as to avoid unnecessary exposure. Finally the results from the experiment are taken from a remote data logger such that no physical contact is required with the experiment whilst the source is present, this allows the results to be reviewed constantly and the experiment checked daily without the need to be exposed to the radioactive source.

4.2.3 Predicted results

The results predicted from this part of the experiment are that the known ELDRS susceptible devices degrade gradually as shown by experiments carried out in published work. It was expected that a change would be seen in the devices suspected to be susceptible and that there be no change in the devices known to be radiation tolerant at the dose rates in use. The changes are expected to be gradual but clear by the end of the four month period when the total predicted failure dose is reached.

4.2.4 Conclusions

This experiment allows for the testing of components at the levels associated with ELDRS and is carried out in a method which makes the results comparable to those published by facilities using methods based on the current MIL 883 standard meaning the results taken have an outside control with which to be compared. The method allows for many devices to be tested at once constrained only by the number of test boards able to fit within the distance set from the measured activity from the source. Finally, full control over the measurements taken and the data recorded is available meaning that the data selected for recording can be chosen to be the same as that available from published works for means of comparison and veracity.

4.2.5 Chamber design

In order to comply with licenses at the university, a Cobalt-60 source no greater than 555MBq can be used. Three, 185MBq, Co-60 sources were ordered from High Technology Sources Limited, UK. These sources would need to be held in a lead castle where the dose rate outside was less than 7.5 µSv h⁻¹.
Figure 71: Model sources

Figure 71 shows model sources which were created to the same dimensions and approximate weight of the ones ordered. This was done so that placement of the sources could be practiced prior to their arrival and to aid in the design on the chamber.

Figure 72: Chamber Design side view
Figures 72 and 73 show the design plan of the chamber to be constructed, with the selected thicknesses of lead the dose rate 1m from the source (1m is outside the shielding) is ~0.7μSv/hr, 10x lower than required.

Figure 74 shows the interior of the actual chamber before the lid is put into position, the lead pot in the centre is where the sources will sit once in position. The large lead container at
the bottom right is where the sources can be moved in the event that the sources need to be secured quickly before the end of the experiment— if there is a collapse, fire, or other emergency.

Figure 75: Complete chamber assembly

Figure 75 shows the chamber with the sources contained in the perspex tube, sealed by a lead rod. There is also the electronic dosimeter to the right which is used to monitor the external dose rate, the data-logger is also visible.
4.3 High dose rate tests

High dose rate tests were carried out at the National Physical Laboratory (NPL) in Teddington, United Kingdom in a similar fashion to the low dose rate tests using the MIL 883 standard. The items under test were 8 AD590KF temperature transducers and 8 LM124 operational amplifiers.

Upon arrival all test components were unpacked and visually inspected. Each component is then tested by inserting it into the relevant test circuit. The data is recorded using a LabJack Ue9-Pro operating at 20-bit resolution. The components were then inserted into a breadboard holder to contain them within the 8cm x 8cm boundary within which the dose from the source will be uniform. The AD590s had their pins bent at right angles to ensure the devices were facing the source aperture. The distance between the surface of the devices to the source exposure aperture was measured so that the dose rate could be calibrated to give 20Gy/hour.

![Figure 76: Stage arrangement at high dose rate facility, NPL, UK](image)

Figure 76 shows the plastic sheets used to raise the stage on which the devices will be placed beneath the opening to the Co-60 source. The distance shown is calibrated to give a dose of 20Gy/hr at the surface of the components. Before irradiation begins the components are placed on the stage and the distances measured to an accuracy of 1mm.

The devices are kept unbiased and with all pins grounded whilst in the holder under irrad-
ation. The irradiation chamber is sealed and the devices are exposed for one hour up to 20Gy. The source is secured and the devices are removed from the test room to an adjacent room where they are tested in turn. Firstly, 5 unirradiated, unmodified AD590KFs are connected in turn to the test circuit and their output is measured and recorded. This is followed by the 4 irradiated AD590KFs, one at a time. The devices are inspected again to ensure they all remain level (the same distance from the source) and returned to the irradiation chamber. The temperature and time taken between stopping the irradiation and re-starting are then recorded and the devices are irradiated for a further 20Gy. This process is repeated to 120Gy after which the devices are left overnight at the same dose rate with the next measurement at 426.5Gy.

The chamber is then reset and the stage raised to give a dose of 60Gy/hr for the remaining 4 implanted AD590KF and the 8 implanted LM124. The test circuit for the LM124s is then connected to the data-logger and the irradiated LM124s are removed from the breadboard in sequence and placed in the test circuit, and then replaced in the breadboard holder after each test before being irradiated as per the AD590s at 60Gy/hr with hourly measurements. Along with the devices, 4 decapped LM124/AD590 which have not been implanted and 4 of each unmodified devices were also irradiated for comparison.
5 Results and Analysis

5.1 Test Parameters and circuits

During the irradiations both the amplifiers and the temperature transducers were unbiased with all pins connected to a common ground.

The four positive, four negative and four output terminals along with the main voltage input and ground pins shown in Figure 77 were all connected through a socket to a common ground with the grounding of each pin tested using a continuity tester before each irradiation. During the implantations, conductive tape was used to further ensure a secure connection to the base plate. This grounding was in accordance with the unbiased test procedures used in the MIL-883 1019 radiation testing standard.

The parameters tested for the LM124 were the closed-loop DC gain and the input bias current, for the AD590 the device was used to collect a temperature reading by measuring the...
output voltage in the test circuit and compared the results to a unmodified sample.

![Diagram of LM124 Closed-Loop DC Gain](image)

Figure 78: LM124 Closed-Loop DC Gain

For the gain measurements, the resistor values of R1 and R2 were altered to achieve gains of 2, 101 and 22. As shown in Figure 78 the arrangement gives a gain of 101, two 10k resistors were used for the gain of 2 measurements and 47k and 1M resistors (R1 and R2 respectively) were used to achieve a gain of 22.2 using the formula \( \frac{R2}{R1} + 1 \) to give the closed loop gain. The input voltage was provided by a stable 0.05V source, which was provided to each of the four amplifiers in each package at the same time. All four amplifiers were connected to a common ground and measurements of the output voltage was measured using the LABJACK UE9-pro at 18bit resolution connected to a laptop. Ground noise and voltage output noise were recorded for the purpose of error analysis. For input bias measurements, two measurements are required which are shown in Figure 79.
Figure 79: LM124 Input Bias Current Measurements

All four amplifiers were measured at the same time, the positive input followed by the negative input with manual switches used to change between measurements. The output voltage is recorded along with ground and reference voltage measurements by the LABJACK UE9 datalogger and the input bias is calculated by taking an average of the positive and negative currents recorded. All resistors used had a 1% tolerance.

5.2 Results of Hydrogen ion implantation

Once all implantations were complete the devices were left to anneal for 48 hours at room temperature before taking measurements to check for functionality. The following implants were conducted and the devices were tested for functionality using the circuits described in the previous chapter.

<table>
<thead>
<tr>
<th>Device</th>
<th>H Implant</th>
<th>No.</th>
<th>Survived</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD590</td>
<td>1.3x10^17</td>
<td>19</td>
<td>18</td>
<td>All devices survived offset, one used as sacrifice to PIXE</td>
</tr>
<tr>
<td>LM124</td>
<td>5.8x10^14</td>
<td>3</td>
<td>3/9</td>
<td>9 amplifiers survived, 3 erratic, reduced functional gain</td>
</tr>
<tr>
<td>LM124</td>
<td>8.5x10^15</td>
<td>5(-1/4)</td>
<td>5/18 (+)</td>
<td>Contained unimplanted region to test, one erratic</td>
</tr>
<tr>
<td>LM124</td>
<td>9.9x10^16</td>
<td>5 (-1/4)</td>
<td>5/12 (+)</td>
<td>Contained unimplanted region to test, 7 erratic</td>
</tr>
<tr>
<td>LM124</td>
<td>3.4x10^17</td>
<td>3</td>
<td>0/0</td>
<td>All amplifiers on all devices erratic</td>
</tr>
</tbody>
</table>

Table 1: Device Test Results after Implantation
Table 1 highlights the results from device tests after annealing. There are 4 amplifiers on each LM124 device, the total number of packages is indicated in the table with “-1/4” to indicate that 1 of the 4 amplifiers was unimplanted and subsequently in the column of surviving devices the “+” indicates that the unimplanted region also survived. For example the $8.5 \times 10^{15}$LM124 implants, 5 LM124 were used and since each LM124 contains 4 amplifiers there are 20 amplifiers in total. One amplifier on one device (-1/4 of an LM124) was purposely not implanted, 18 out of the 20 amplifiers survived the implantation, 1 was erratic (gave widely fluctuating readings when tested) and 1 was not implanted (+), leaving 18 to be irradiated.

All the higher implanted amplifiers no longer functioned correctly, most of the remaining amplifiers survived and all of the temperature transducers survived with a minor offset ($\sim 12$ mV) in measured output compared to unimplanted samples.

### 5.3 Results of low dose rate irradiations

Four LM124 which had been implanted to $9.9 \times 10^{16}$ H/cm$^2$ each containing 3 working amplifiers were placed into a breadboard with all pins grounded, four implanted AD590, four decapped unimplanted LM124/AD590, and four of each unmodified were all added to the grounded bread-board. The boards were placed in the chamber and the sources added.

The devices were unbiased whilst irradiated and powered by 5V as per the circuits when measured at $\sim 10$, 20, 40, 80 and 100 Gy at 15 $\mu$Gy/s, the LM124 were tested with gain = 2, 22.2 and 101.
Figure 80: AD590 Low Dose Rate response (Vout)

Figure 81: LM124 Low Dose Rate response (Gain=2)

Figure 80 shows the response of the AD590KF to low dose rate irradiation. The implanted transducers suffer from an offset which remains constant over temperature (tested at 5, 25, 75 and 125ºC. The unmodified devices degrade by 7% whilst the implanted devices degrade
by 14% with the majority of that degradation appearing after 75Gy total dose. Whilst it is already known that the AD590 is susceptible to ELDRS and as such the 7% degradation was expected, the offset from the implanted transducers indicate that the implantation procedure has caused physical damage to the device. When calibrated both the implanted and unmodified AD590 function correctly and report varying temperatures and the change between temperatures correctly indicating this offset does not affect the primary function of the device and is a uniform error which does not affect the device’s ability to detect temperature changes once calibrated. The increase in degradation in the implanted sample after 75Gy may indicate a shift in the threshold dose for ELDRS sensitivity which would be consistent with results from Adell et al [ADEL-07].

Figure 82: LM124 LDR response (Gain =22.2)
Figures 81, 82 and 83 show the response of four sets of LM124 at three different closed-loop gains, 2, 22.2 and 101, a maximum of 20% degradation in amplification is seen from the highest implanted amplifier (9.9x10^{16}\text{ions/cm}^2) whilst the decapped device and the lower implanted devices behave similarly, though there is reason to believe that the implanted device will degrade further since previous studies on the ELDRS response of the LM124 show a continued degradation under low dose rate irradiation between 50Gy and 300Gy [SEIL-04]. The devices show identical (within error) degradation at each gain level which indicates the degradation recorded is due to a failure in the amplifier. The equipment was checked with a sample of non-irradiated devices and unimplanted regions of sacrificial devices to check for systematic errors in the test circuits and equipment. Error bars are shown on Figure 80 indicate the standard deviation in results and are removed for clarity on Figures 82 and 83.
5.4 Results of high dose rate irradiations

5.4.1 AD590

Figure 84 shows the degradation of the AD590KF. These devices were unmodified and still in their packaging. The degradation is steady, there is an apparent fluctuation between 20 and 40Gy however this does not continue and the device degrades by approximately the same amount as in the low dose rate experiments but after 5x the total dose.
In Figure 85 the degradation of the Hydrogen-implanted AD590s is shown. Given the offset the device appears to degrade much slower than the standard packaged device showing only a 3% degradation.

Figure 86 shows the response of the H implanted AD590 to very high dose rate irradiation, there is greater degradation shown than the implanted transducers at the 20Gy/hr dose rate but less change than in the unmodified samples. It is possible that secondary radiation caused...
by the interaction with the Gold lid is causing further degradation in the unmodified devices, or that the damage caused by the implantation provides more recombination sites for electron-hole pairs caused by the gamma irradiation which reduces the total ionisation damage.

5.4.2 LM124

Figure 87: LM124 Unmodified and decapped response to 60 Gy/hr

Figure 87 shows the response of the unmodified LM124 and decapped but unimplanted LM124 to Co-60 irradiation. The unmodified samples are affected to a similar level as the low dose rate unmodified samples but at 3x the total dose. The decapped LM124 show a 50% degradation at all levels of tested gain which constitutes the greatest degradation measured in any unimplanted amplifier. The packaging has a negligible effect on the dose from gamma radiation thus this degradation must come from the device’s exposure to the outside environment aside from the gamma radiation.
In Figure 88, the radiation response of unmodified LM124 is presented alongside the implanted LM124 at two different implant levels. The lower implant level shows a similar amount of total degradation to the unimplanted samples. This could be explained if the implantation process caused damage, which is does, followed by the hydrogen annealing out or being in a state where it is unaffected by the gamma radiation. The lower bound for permanent ion implantation was established earlier to be $10^{15}$ ions/cm² thus this may be consistent.

The higher implantation dosed amplifiers appear to degrade in a similar fashion to the un-implanted, decapped, amplifiers from figure 68 however their degradation is 10% greater.

5.4.3 Annealing

When irradiating at high dose rates, in order to compare with the lower dose rate responses and distinguish between true dose rate effects and time dependant effects the high dose rate devices are left for an amount of time such that if the total dose is averaged over that extended time it would equal the dose rate of the lower dose rate tests, or indeed the space environment as per the current standards. As such all devices were left to anneal unbiased at room temperature in
a hermetically sealed container until the average dose rate was equal to the dose rate of the low
dose rate experiments previously described.

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>HDR</th>
<th>Anneal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>1.69</td>
<td>1.63</td>
<td>1.68</td>
</tr>
<tr>
<td>Decapped</td>
<td>1.69</td>
<td>1.62</td>
<td>1.68</td>
</tr>
<tr>
<td>Implanted</td>
<td>1.52</td>
<td>1.43</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Table 2: AD590 Post-HDR Response after Anneal (Vout)

Table 2 shows the measured output of the AD590 after being left to anneal. As can be
seen the unmodified and the decapped devices show almost identical recovery after annealing
implying both are sensitive to high ionisation damage but that the defects caused are low energy
which are rectified by thermal excitation within the device. The implanted device also shows
some recovery, but not to the same extent as the unimplanted devices which implies permanent
damage has occurred.

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>HDR</th>
<th>Anneal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unmodified</td>
<td>2</td>
<td>1.81</td>
<td>1.89</td>
</tr>
<tr>
<td>Decapped</td>
<td>2</td>
<td>1.01</td>
<td>1.51</td>
</tr>
<tr>
<td>5.8x10 14</td>
<td>1.25</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>8.5x10 15</td>
<td>2</td>
<td>0.81</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Table 3: LM124 Post-HDR Response after Anneal Amplification (G=2)

In Table 3 the LM124 have annealed and there has been some recovery in all devices. The
unmodified device and the lower level implanted device behave similarly, given the initial off-
set. The decapped sample shows significant degradation followed by over 50% recovery whilst
the higher implanted LM124 shows less than 20% recovery after room temperature annealing.
Similar to the AD590, the implanted devices at the higher levels appear to recover less after
annealing than the decapped samples and show significantly more degradation compared to the
unimplanted standard samples.
5.5 ELDRS response

Figure 89: LM124 ELDRS response

Figure 89 shows a comparison between the measured input bias current at low and high dose rates with and without hydrogen implantation.

The fit used in Figure 89 is for illustrative purposes only as they show the separation between the high and low dose rate measurements, the points should be used for comparison but the lines remain as a visual guide.

The LM124 when compared to high dose rate irradiation at 60Gy/hr up to 100Gy showed an enhancement factor of 1.6x at low dose rate, an enhancement of 1.3 at high dose rates following implantation, 1.1x for high dose rate when decapsulated but unimplanted, 2.6 for decapsulated low dose rate and a maximum of 2.7x for implanted low dose rate irradiations. At low dose rates both the unimplanted decapsulated samples and the implanted samples showed a similar enhanced response compared to the measured ELDRS response for unmodified samples. At high dose rates the implanted samples showed an increased degradation compared to both the standard samples and the decapped samples. The difference between the responses at high
and low dose rates regarding implanted and decapsulated samples is a time dependant effect. At low dose rates the samples are effectively undergoing an annealing process during which time hydrogen contamination is affected by exposure to the atmosphere and sufficient time is given for an equilibrium state to be reached between liberated hydrogen due to implantation and external contamination which is not the case for the high dose rate irradiations which are completed within 70 hours of implantation. After annealing from high dose rate irradiation the decapsulated unimplanted samples recover significantly more than the implanted samples, shift in the degradation of the implanted samples at high dose rates brings the measured actual degradation closer to that of low dose rate tests.

Figure 90: AD590KF ELDRS response

Figure 90 shows the change in measured output of the AD590KF compared between dose rates and presence of implanted hydrogen.

The AD590KF when irradiated at low dose rate shows a steady increase in the change in output voltage with total dose and appears linear, whilst there is error in the results due to deviation between measurements and fluctuations in room temperature it does appear that there is a distinct increase in degradation between 20Gy and 40Gy, however with only two measurements before 40Gy there is insufficient data to draw firm conclusions on the source of this apparent
increase. When implanted this initial steady increase in the change in output voltage continues on until approximately 75Gy where there is a significant increase in degradation, greater than that seen for unimplanted low dose rate irradiations. Although there is a delay before this increase the degradation at low dose rates with and without implanted hydrogen is greater than all measured degradation at both high dose rates. The shape of the degradation for both high and low dose rates without implantation is in agreement with previous published work (Figure 89). Compared to measured damage at 20Gy/hr high dose rate tests to 100Gy total dose there is an enhancement factor of 3.4 at low dose rate, this increases to 5.9 with hydrogen implantation. Interestingly at high dose rate the damage at this level is actually reduced by a factor of 0.3 with hydrogen implantation.

Both sets of devices showed a significant increase in degradation when they had been delidded compared to remaining sealed. Similar results were found in earlier research which suggested that hydrogen contamination from the surrounding atmosphere could be responsible for this effect, which leads to the conclusion that the addition of hydrogen to a device will increase its ELDRS sensitivity. In these experiments it was found that the AD590KF when implanted with protons appeared to degrade less up to 100Gy at the 20Gy/hr dose rate, but the same effect was not observed for the low dose rate tests. A potential explanation for this is that the main source of hydrogen contamination for the AD590 comes from the flatpack packaging, as discussed during the literature review. This hydrogen diffuses into the device where it remains until exposed to ionising radiation at which point hydrogen cracking and subsequent proton release will occur which leads to the interface trap formation ultimately responsible for the low dose rate response. The protons cause the release of hydrogen from Si-H bonds at the interface leaving a hole trap and molecular hydrogen which then can be cracked and continue this process. During the implantation process, protons were introduced to the de-lidded device, these implantation protons were accelerated to an energy where they would reach the interface depth and remain, at this point the implanted protons were capable of de-passivating the Si-H bonds already present at the interface, releasing molecular hydrogen into the device. Since the devices were delidded, this molecular hydrogen could then diffuse out of the device and the traps created near the interface are known to anneal with time. TSC measurements would be required to confirm whether this process did occur which would require further testing. At low
dose rates sufficient time is given for trapped implanted protons to be released and contribute to the increased ELDRS effect seen in the devices which may also explain the sudden increase in degradation in the implanted low dose rate tests when the deeper trapped protons reach the interface boundary. This method for accelerating ELDRS assumes that hydrogen contamination causes the ELDRS effect in devices. The implanted protons cause the immediate release of hydrogen from Si-H complexes which gives rise to an exaggerated ELDRS effect in devices which are contaminated with hydrogen. For devices which are not contaminated the effect of proton irradiation at this level would cause and ELDRS-like effect to be observed initially, until they are either passivated or permanently trapped in the device leading to a stable reduction in electrical parameters, as seen in the case of the implanted LM124 at $10^{14}$ protons/cm$^2$ (below the stable limit for protons in Si thus allowing proton re-distribution).

5.6 Comparison with control samples

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>HDR</th>
<th>Anneal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unmodified</td>
<td>2</td>
<td>1.81</td>
<td>1.89</td>
</tr>
<tr>
<td>Decapped</td>
<td>2</td>
<td>1.01</td>
<td>1.51</td>
</tr>
<tr>
<td>8.5x10$^{-15}$</td>
<td>2</td>
<td>0.81</td>
<td>1.16</td>
</tr>
<tr>
<td>Control (Implanted)</td>
<td>2</td>
<td>1.00</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Table 4: LM124 decapped control comparison (Amplification G=2)

The ELDRS-free LM124 used as a control did not exhibit degradation during the low dose rate testing which is expected given National Semiconductor has manufactured them for this purpose, at high dose rates they performed similarly to the unmodified COTS components. However, as Table 4 shows, once the devices have been delidded they react in a similar fashion to the delidded standard samples at both high and low dose rates. This agrees with the conclusions made by Pease et al [PEAS-10] where it was found that removing the packaging of the device negated the ELDRS-resistant quality. What is noted in this experiment though is that the control devices have been implanted to the same degree as the standard device on Table 4 yet it shows greater recovery. The difference is small, however it follows that if hydrogen contamination was kept to a minimum during the manufacturing process of this device, less molecular hydrogen would be created when exposed to the ion beam, thus one would expect the response to be closer to
that of a standard delidded device as opposed to a standard implanted device. It should be noted however that given it is known that molecular hydrogen can diffuse into a device from the atmosphere, unless the device has a p-glass nitride passivation, given sufficient exposure both the exposed standard LM124 and the exposed ELDRS-free LM124 would be expected to show ELDRS as in the Pease et al study[PEAS-10].
5.7 Comparison with published data

Figure 91: Comparison between published [ADEL-07] results for AD590 and results from this thesis

Figure 91 shows the modified results from published AD590 irradiation experiments where the amount of hydrogen present in the devices was measured [ADEL-07]. It was found that there was a correlation between the amount of hydrogen present in the device and the severity of the degradation. The more molecular hydrogen present, the greater the degradation at both high
and low dose rates. The data from the published work and the results from the experiments carried out in this PhD in figure 89 show similarities in that both low dose rate tests show increased degradation compared to high dose rates and there are clear groupings between the two, additionally, there is a visible distinction between hydrogen concentrations in both high and low dose rate tests and the observed error appears similar between both sets of results; whilst similarities are apparent, it should be noted that the total dose for the published work is far greater than that for the experiments described here. Whilst it is true for the LM124 from the experiments conducted in this thesis that at high and low dose rates greater hydrogen contamination matched greater degradation, the results gathered for the AD590 do not completely agree. In the implantation experiments at high dose rates it was found that the devices degraded less than the unimplanted samples, it has been suggested that this is due to the presence of the packaging, after annealing the results from the implantation experiments concur with the ones above. Additionally both experiments found greater degradation at low dose rates compared to high dose rates, and that this effect was further exaggerated by the presence of hydrogen.

5.8 Criticisms

Although these results represent the initial move into an area of using ion implantation for accelerated ELDRS device testing, a number of criticisms can be drawn from the experiments conducted which should be addressed in future research in this area.

- Only two (three) devices were used in these experiments, from this research it cannot be concluded that all devices will behave in the same manner when implanted with hydrogen ions and irradiated, devices from all bipolar groups should be implanted and tested before concluding that this test method is viable.

- The effect of passivation has not been accounted for, the literature review showed that the same device when passivated by different materials can respond differently to low dose rates and that this can affect whether a device is ELDRS-susceptible, additionally other than from reviewing the SRIM simulations, the extent of the damage to the passivation from the de-lidding process and the ion implantation is not known. If the passivation is responsible for limiting hydrogen ingress and it is damaged by these processes, this would
affect the device’s response to ionising radiation.

- The method used for implantation does not allow for the measurement of hydrogen present in the device directly, since hydrogen ions are being implanted, when the RBS (Rutherford Backscattering Spectra) are being collected the hydrogen signal is filtered out, in order to determine the amount of hydrogen present in the device initially before implantation, either TSC measurements or another ion should be used so that the hydrogen content can be assessed rather than inferred.

- The results are not consistent between the LM124 and the AD590, it was found that the removal of the package had a greater affect on the AD590 response to radiation than the ion implantation (until after annealing), which brings in to question the practical application of the results for the AD590 as the presence or absence of the package had a greater effect on the initial results than the variable being tested. It is thought that the inconsistency is due to the presence of the Gold on the AD590 package which would cause a greater shielding effect than the LM124 packaging which was not metallic.

- This method for assessing the ELDERS susceptibility of devices is both expensive, requiring the use of a particle accelerator, and time consuming, given that the ion beam may need to be targeted manually throughout the course of the implants. It is also less likely that companies will have access to an ion beam than they will to the standard equipment required for the MIL883 1019.8 radiation testing. Both the delidding and the implanting necessarily causes physical damage to the device, which is currently avoided when using standard testing methods.

- The synergistic effects of ion implantation and gamma irradiation need to be studied further, not only for the purpose of this method, but because the typical space environment in which these devices will be used is better represented by proton and electron irradiation as opposed to constant gamma flux, this may lead to proton implanting/damage being used in conjunction with gamma irradiation tests in the future, however at present, in order for the results from the experiments conducted in this thesis to be accurately compared with other radiation testing results, more needs to be known of the synergistic effects involved.
• A limited number of devices were tested during these experiments, this was due to the number needed to test at which concentration, time, energy and acceleration potential would be appropriate for the ion implantation. In order to produce more reliable results it would be recommended to repeat the experiments performed here, at the values found to be suitable for implantation, with 30 or more components at each stage.

• Once the lids of the devices have been removed, they are exposed to the atmosphere and vulnerable to contamination from water vapour and molecular hydrogen, even though devices were stored in a hermetically sealed container, they were still exposed to the external atmosphere during the course of the experiments.

• Due to the nature of ion implantation, the exact number of ions implanted is not known until after the implantation is complete and the data can be analysed, it was found during the course of these experiments that implants could be an order of magnitude greater than intended and this is not known until the cycle of implantation is complete.

• There is a risk that any previously untested device will be destroyed by the implantation process immediately, even at the lowest level of implantation, this method should be categorised as destructive and therefore unsuitable for devices where there are a limited number

• Due to the need to remove the packaging from devices prior to implantation, this method negates the testing of devices which are proposed to be radiation-hard since this attribute is associated with both the method of packaging and the package itself.
6 Conclusions

6.1 Summary of results

The radiation environment in space has been discussed in this report. This environment can be simulated using available software and the results are known to compare well with actual flight data. The radiation in space has an effect on electronic devices and these effects can be split into instantaneous single event effects and long term cumulative total dose effects. Although known since the 1990s it has only been since 2009 that Enhanced Low Dose Rate Effects have become a threat for the space industry as indicated by their inclusion in the most recent radiation section of MIL-STD-883-1019.7 testing standard which in terms of its radiation testing is very similar to most total dose testing regimes used today. There is an ongoing desire to use commercial technology in the space industry as it is less expensive than purpose built components and is updated at a faster pace, due to this pace an accelerated radiation testing regime is required to ensure the new devices can survive the radiation environment in space. There is currently no universally accepted accelerated test regime which takes into account the ELDRS effect and there are susceptible components which cannot be replaced by technology thought to be resistant to ELDRS.

It has been found that hydrogen introduced during the manufacturing process of semiconductors has a great affect on ELDRS susceptibility of devices and for the first time it has been proposed that hydrogen implantation is used to probe devices to study the ELDRS effect.

These experiments have demonstrated the following:

1. Hydrogen can be implanted into bipolar devices successfully
2. The lower bound for hydrogen implantation is confirmed to be $10^{15}$ ions/cm$^2$, beneath this defects are energetically unfavourable at thermal energy levels
3. The upper bound for hydrogen implantation is not constant through devices, $10^{17}$ H/cm$^2$ is acceptable for AD590 whilst above $10^{16}$ for LM124 (and hence LM224/324) causes more device failure than successful implants
4. Decapped LM124 show a greater response to gamma radiation than packaged components
5. Decapped AD590 show less degradation to gamma radiation that packaged components
6. Both devices degrade more at low dose rates than higher dose rates
7. Both decapped devices after annealing show recovery similar to unmodified devices

8. Both devices show significantly less recovery after annealing if implanted with hydrogen when compared to decapped and unmodified devices

9. The LM124 after implantation, HDR irradiation and annealing recovered to the same level as hydrogen implanted LM124 at the very low dose rate

If high dose rates and annealing with implanted hydrogen recover to the level which would be reached with a low dose rate irradiation, this can constitute an accelerated testing method, providing that the level of implanted hydrogen is sufficient to remain in the device, is implanted to a depth which is at the Silicon/oxide boundaries and is insufficient to cause device failure—most likely through delamination of layers.

The results from these experiments could form an accelerated testing method if the following conditions are met: Firstly, that hydrogen can be successfully implanted into more devices without the process itself causing device failure, and secondly if it is found that the devices degrade in a similar fashion at high dose rates (allowing for annealing) as they do at low dose rates. Care must be taken to ensure the amount of hydrogen implanted is sufficient to persist in the device and that the energy required to implant the hydrogen is sufficient to reach the required depth without causing device failure, the primary concern is the damage caused by the implantation itself and whether this is feasible for devices beyond those tested in this thesis.

6.2 Investigating the role of hydrogen in ELDRS using ion implantation

This PhD research has demonstrated that protons can be implanted at sub-device level target sites in components and that this implantation can affect the operation of the device. In the case of the LM124 it was established that below $10^{15}$ H/cm$^2$ the implantation process caused physical damage to the device leading to a uniform change in characteristics, the gain was uniformly reduced but there was no measurable difference between the degradation of the devices once exposed to ionising radiation at both high and low dose rates between devices which were implanted below $10^{15}$ H/cm$^2$ and devices which had been decapped and exposed to the environment after taking into account the initial parameter shift. The upper bound of $10^{17}$ H/cm$^2$ for the LM124 was established as at this concentration few devices were surviving the implantation procedure, however at this level all the AD590KF survived which indicates that the upper
bound of ions capable of being implanted is device dependant. The lower bound remains at $10^{15}$ H/cm$^2$ as below this level there is sufficient thermal energy present at room temperature for the implanted ions to escape in Si/SiO$_2$. The experiments on the LM124 has shown that at above $10^{15}$ H/cm$^2$ when implanted, H ions will remain where they are targeted. The LM124 internal structure is such that there are four discrete amplifiers drawing from one input voltage and common ground, when three of the four amplifiers were implanted over an area which approached but did not encroach upon the common power and ground section in the centre of the device, the three implanted amplifiers performed at an altered gain level consistent with the remaining implanted LM124 devices, whereas the unimplanted amplifier on the same device functioned identically to the unimplanted decapsulated devices. This shows that the ions are well targeted and do not cause sufficient damage outside of the targeted area to affect the functioning of the device as a whole, and that at low temperatures (room temperature) the effect of atmospheric contamination over the time period of the experiments was minimal. For test devices where the implantation area was large enough to encompass the centre of the LM124 device, the device was destroyed by the implantation, showing that the chosen target location is important and that different locations can survive different levels of implantation. In summary, it has been found that hydrogen ions can be successfully implanted into specific areas of a device in a manner which leaves the device able to function and the subsequent ELDRS effect to be studied, that there is a minimum concentration of hydrogen ions which can be implanted which is determined by the capabilities of the implantation facility and the implant target material, for the case of the tested devices and Si/SiO$_2$ based components the lower bound is $10^{15}$ H/cm$^2$, the upper bound for the hydrogen ion concentration is device specific and on a sub-device level there is an upper bound depending upon where in the device the ions are targeted. These results have demonstrated the feasibility of using a proton beam to probe devices in order to study the ELDRS effect at a sub-device level by allowing for the targeting of a hydrogen ion beam at sites of dangling bonds and forming molecular hydrogen at device interfaces consistent with current theories placing the cracking of hydrogen in these locations as responsible for ELDRS.

**Further work:**

- Use deuterium and helium to study mass and charge effects -more devices: Deuterium has
twice the mass of a hydrogen ion but would bond in a similar fashion to the dangling Si bonds, this would make it easier to isolate were one to wish to perform detailed implantation scans to confirm that implanted ions remain at the target location and over what time period this is true. In a similar way, helium could be used which has twice the charge of a hydrogen ion and it would be interesting to investigate what effect this would have on the ELDRS response.

- Investigate lower current longer time implants/ higher shorter: Raising the implantation current reduces the amount of time required to perform the implantation but also increases the likelihood of damage to the target device since more ions are being implanted per second, lowering the current would reduce the damage however the process would take longer and the effect of having the delidded devices in a vacuum would have to be considered more carefully with regard to outgassing.

- Probe devices to map different levels of tolerance to implantation: In this PhD the devices under test were implanted in particular target areas, it would be useful to extend this by implanting at one energy, and ion concentration in different areas of a device to ascertain whether the predicted regions for ELDRS sensitivity are the only regions or whether other areas previously unconsidered could lead to ELDRS being observed following implantation. This process could then be repeated at various energies (depths) until the entire device is characterised in this manner.

- Perform TSC (Thermally Stimulated Current) measurements before and after H ion implantation to identify the relative change in molecular hydrogen concentration: TSC measurements could be used, destructively, to ascertain the concentration of molecular hydrogen in a sample of devices from a batch in an effort to predict the typical level of hydrogen contamination for a particular device from a particular manufacturer and manufacturing facility. These measurements could also be performed following ion implantation to see how the concentration is affected, a large sample would be required for the measurements to give a reliable assessment since each measurement would destroy the device and thus could not be repeated on exactly the same component before and after implantation.
6.3 Investigating hydrogen ion implantation on ELDRS susceptibility using high and low dose rate testing

Pease et al in their published research [PEAS-09, PEAS-10] have put forward a method for using molecular hydrogen as an accelerated ELDRS testing method. The method involved decapping components and then storing them in pressurised vessels with molecular hydrogen present at varying atmospheric percentages which encourages the hydrogen to diffuse into the device to varying degrees depending upon the external concentration. Tests were done between 1% and 100% external molecular hydrogen concentration and this was found to induce the ELDRS effect in devices, including devices which were previously ELDRS-free. The conclusion of their research was that exposure to molecular hydrogen in this manner cannot be used as an accelerated method, as parts which are qualified as ELDRS-free after being decapped and exposed to molecular hydrogen then exhibited ELDRS, however in itself this result confirmed that the presence of molecular hydrogen in a device is a variable which determines whether a device will be susceptible to ELDRS. In the research in this PhD, rather than introducing molecular hydrogen into the device under test by design, the hydrogen ion beam is used to probe the interfaces in a device such that if there is hydrogen contamination in the form of dangling Si-H bonds, this proton beam will cause the formation of molecular hydrogen within the device, whereas if during manufacturing steps were taken to eliminate or reduce hydrogen contamination, there would be few dangling hydrogen bonds present with which to form molecular hydrogen from the hydrogen ion beam. Thus the amount of molecular hydrogen formed during the ion implantation process is not independent of the initial presence of hydrogen in the device unlike the hydrogen soaking method where an equilibrium is reached between the atmosphere and device regardless of initial hydrogen contamination. Whilst the implantation process itself introduces hydrogen to the Si/SiO2 interface, further research would be required to see the probability of this process forming Si-H bonds and thus introducing the effect which is to be studied. The data from the experiments conducted does not appear to support the conclusion that at the implant energy used this was occurring as the ELDRS-free devices did not show ELDRS after implantation, further research in this area should be conducted to find out at what energy and in what conditions this result holds valid.
During the high and low dose rate irradiations it was confirmed that both the AD590KF and the COTS LM124 both show evidence of ELDRS as expected, and the radiation tolerant ELDRS-free LM124 did not show ELDRS when unmodified. The results from both the high dose rate tests and the low dose rate tests show the effect of the packaging on the response of both devices to radiation. Both devices and the control ELDRS-free LM124 showed increased degradation when the device was delidded compared to an unmodified device. The exception being the AD590KF during the high dose rate tests where the decapped devices degraded less than the unmodified devices, however after annealing the implanted devices recovered less than the unmodified samples indicating the time dependant nature of the degradation. At high and low dose rates, the LM124 which had been implanted with hydrogen both showed an increase in degradation, the ELDRS effect was more prominent at a lower total dose compared to the control devices and the degradation at high dose rates was also more exaggerated. The implications of these findings are that although devices will inherently be ELDRS susceptible due to being bipolar and processed using a method which causes hydrogen contamination, the packaging itself should not be dismissed during testing. ELDRS-free devices have been shown to be susceptible if their packaging is removed thus any effective testing method should either test the device with the packaging intact, or perform further tests to ensure the effect of the packaging is taken into account. It cannot be said that devices will always degrade more when the packaging is removed, as with the AD590 the additional interactions between the incident radiation and the packaging caused the device to perform worse than predicted compared to the delidded samples. Again the conclusion from this is that an effective testing method would ideally not remove the device from its packaging, or test the device with and without packaging if its removal is necessary, additionally, if a device is required but fails the standard radiation testing, it would be appropriate to test the same device in an alternate package.

Further work:

- Since differences were noted between the response to radiation at 20Gy/hr and 60Gy/hr it would be worthwhile conducting further experiments to find whether there is a maximum dose rate (hence minimum time) at which devices can be tested and then the effect of hydrogen assessed after annealing
• To investigate whether the deleterious effect of packaging on some devices under gamma irradiation also occurs under high dose rate nuclear and beta radiation as typified in an orbital environment

6.4 Deriving a new accelerated test method for ELDRS

The results from this PhD can be used to suggest an alternative to the step-stress method of accelerated ELDRS testing, and specifically allows for the probing of sub-device regions such that individual components in a device may be tested independently for ELDRS susceptibility. Using the knowledge obtained through this research a preliminary ELDRS accelerated test method can be put forward. Initially pre-selection criteria can be employed to select those components most likely to be ELDRS susceptible, it is assumed that the devices will either be bipolar in nature or there is reason to suspect that they could be susceptible, for example, MOS devices with large oxides. The following flow chat shows the selection criteria.

The switched dose rate method is currently suggested as an accelerated test method, and is employed by at least one company (Thales Alenia Space)[MARE-14] as the recommended method for ELDRS testing. The switching method as used requires testing components at high dose rates of 0.01Gy/s for one day, low dose rate tests at 10\(\mu\)Gy/s for 23 days and reference tests at a continuous low dose rate. The total time required is approximately one month, the total dose is 1kGy(Si) and electrical measurements are taken every 200Gy. A total of 5 switches are made between high and low dose rates and 60 devices are required if testing biased and unbiased conditions with 5 devices at each step.

At present, if the hydrogen ion implantation method is used as an accelerated test regime, the following method would be used:

• Firstly, as with all methods the devices would be electrically characterised.

• Simulations would be conducted using known or estimated passivation composition and device thickness to estimate required implantation acceleration potential

• Device is delidded

• A single device is placed in the ion beam at the minimum estimated acceleration potential,
backscatter data is used to reveal whether the required depth has been reached, if a greater acceleration potential is required then it is increased until the features of interest in the device are seen.

- The region of interest is identified within the device

- Sacrificial devices are used to establish optimum ion concentration, test at $10^{15}$, $10^{16}$ and $10^{17}$ H/cm² and functionality following implantation, the precise number of implanted ions can only be known after implantation with the precision limited by the time and energy constraints of the facility

- Devices under test implanted to selected concentration

- Devices left to anneal at room temperature for 48 hours in hermetically sealed environment followed by electrical tests

- Devices irradiated at 60Gy/hr for 17 hours to reach 1kGy total dose, electrical tests taken every 20Gy or as required

- Devices left to anneal for 168 hours and final measurements taken

1kGy total dose was selected for direct comparison with the suggested switching method, for the purpose of comparison if both biased and unbiased measurements are required and 5 devices for each are used, the number of devices required will be: 1 device to test acceleration potential 3x3 devices to test ion concentrations 10 devices to implant (5 for biased 5 for unbiased) 10 devices as reference (5 for biased 5 for unbiased) 10 devices as decapped references (5 for biased 5 for unbiased)

Totalling 40 devices up to 1kGy in 11 days, this number could be reduced as research indicates ELDRS susceptible devices show more degradation when in an unbiased configuration.

If the results of the LM124 in this thesis are representative of the behaviour of ELDRS susceptible devices then one would expect to see a difference between the delidded and implanted devices before annealing after the high dose rate irradiations and the data following annealing would confirm by assessing the recovery of the device. If the decapped device recovers back to
its initial state whereas the implanted one does not then it would be concluded that the device is ELDRS susceptible.

It has been concluded that an accelerated ELDRS test would preferably not remove the device from the package, which gives the switching method the advantage. However, the package is either a source of hydrogen contamination or a method for keeping atmospheric hydrogen from contaminating the device, thus if you remove the package and expose the device to hydrogen either by soaking or implantation you can confirm whether the device itself would be susceptible to ELDRS if contaminated or not, if a device is removed from its packaging and probed with a hydrogen ion beam and then does not exhibit enhanced degradation under irradiation one can confirm that the device is intrinsically ELDRS free regardless of packaging. The switching method is currently more reliable than the method proposed in this thesis as it has been tested and applied on a variety of devices and confirmed to be reliable; the hydrogen ion method needs to be thorough tested and scrutinised on a wide variety of devices before it can be considered a reliable method, at this stage it is a preliminary step towards an accelerated method and will require refining. The ion implantation method at present does not require a low dose rate test which is why it can be completed in less time than the switching method, it also requires far fewer devices. The number of steps taken in the switching method correlates to the reliability of the results. The more steps taken the closer the resulting constructed low dose rate curve is to the actual expected low dose rate curve, if the device’s response to low dose rates is not known, or it is known to be non-linear, then the number of switches needs to be increased to maintain an accurate representation of the low dose rate response which may make the switching method financially difficult for higher priced devices requiring testing. The switching method is currently suitable for end-users to test devices in order to ascertain whether the device is ELDRS susceptible, whereas in its current form, the ion implantation method is better suited to manufacturers for testing the sub-device level structure of their products for ELDRS susceptibility and so can be used in designing devices which are intrinsically ELDRS-free by locating and subsequently altering areas of a device found to be susceptible.

In order to bring the hydrogen implantation method into a fully fledged testing regime, more devices need to be tested, the range of implantation energies and concentrations would need to be investigated in order to find a relationship between the device and the ideal implant
concentration, and the relationship between implantation and post-irradiation annealing should be studied to ascertain at what point measurements are best taken and understand the underlying mechanisms using TSC measurements to profile hydrogen concentrations over time.
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145


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147


153
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162