

***STUDY OF RADIATION INDUCED EFFECTS
IN SEMICONDUCTOR DEVICES***

A Thesis

Submitted for the Degree of

Doctor of Philosophy

In the Faculty of Science

BY

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Department of Physics
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September 2004

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Under the Guidance of

Dr. Ramakrishna Damle

Dr. M. Ravindra



Department of Physics
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September 2004

Dedicated To

My

Motherland

DECLARATION

I hereby declare that the work reported in this thesis is entirely original and has been carried out by me independently in the Department of Physics, Bangalore University and ISRO Satellite Centre, Bangalore under the guidance of Dr. Ramakrishna Damle, Reader, Department of Physics, Bangalore University and Dr. M. Ravindra, Division Head, Components Division, ISRO Satellite Centre, Bangalore. I also declare that this work has not formed the basis for the award of any Degree, Diploma, Fellowship, Associateship or similar title of any University or Institution.

September 2004
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CERTIFICATE

This is to certify that the thesis entitled ***STUDY OF RADIATION INDUCED EFFECTS IN SEMICONDUCTOR DEVICES*** submitted by Sri. ***Shrinivasrao R. Kulkarni*** for the award of the degree of ***Doctor of Philosophy*** in the Faculty of Science, Bangalore University, Bangalore, is based on the work carried out by him under our guidance and supervision. This thesis or any part of it has not been previously submitted, to the best of our knowledge, to any University or Institution for any other degree or diploma.

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P R E F A C E

Explosive growth of electronics in the later half of 20th century has made it possible to use electronic systems in applications like nuclear reactor and space system instrumentation. However, devices and instruments operating in these areas are prone to radiation effects wherein a high density of high-energy radiation exists. Hence, when semiconductor devices operate in such a radiation environment (for example satellite), the electronics of the space systems display changes in the electrical characteristics. These changes can have significant effect on the performance of the devices and circuits operating in the radiation environment. Hence, it is essential to know the changes in the device characteristics due to radiation effects, so that specific design margins can be built either into the devices or in the circuits to make them survive and continue to operate in the radiation environment. In the past two decades, intensive investigations of radiation hardness of variety of semiconductor devices have been carried out in order to analyze the performance changes of individual devices and to find better design strategies and to develop radhard device technologies. Thus the study of radiation induced effects on semiconductor devices has emerged as an active field of research and development and various space agencies around the world are engaged in this field.

When semiconductor devices are exposed to radiation (viz. γ -rays, X-ray, electrons, neutrons, protons or heavy ions, etc.) they undergo severe degradation. The damage or degradation may be permanent or transient. The degradation behaviour is a complex process and is dependent not only on the nature of the device but also on the radiation characteristics viz., dose, dose rate, species and the energy of radiation. The study of the

effect of ionizing radiation on semiconductor devices is very important both from the academic as well as technological point of view. Academically it is very important to have an understanding of the physical mechanism of the damage process and technologically it is important to assess the device performance when they need to be operated in the radiation environment. Excellent literature is available on effects of radiation viz., γ -rays, neutrons, electrons, protons, heavy ions on variety of semiconductor devices including Bipolar Junction Transistors (BJT's), Metal Oxide Semiconductor (MOS) devices and Complimentary MOS (CMOS) devices. However, the basic mechanism of radiation-semiconductor interaction leading to device degradation is not yet completely understood. While the study of radiation induced effects in CMOS and integrated circuits (ICs) is more complex, the study on 3-terminal semiconductor device (BJT) can provide useful insight into the mechanism of degradation. Keeping this in mind, we have undertaken a study of radiation induced effects in a basic semiconductor device, namely, BJT. BJTs continue to play an important role in integrated-circuit technology, viz., in analog or mixed signal ICs and BiCMOS circuits because of their current drive capability, linearity and excellent matching characteristics. Many of the BJTs and bipolar integrated circuits, which are not available in radiation hardened version, are still being used in space systems. Therefore it is mandatory to characterize the devices for radiation induced effects. Further, investigations on radiation-induced effects on devices indigenously made in India, to our knowledge, have not been fully carried out. It is thus important to establish radiation-induced response of these devices in comparison to other vendor's parts of the similar family.

This thesis involves the study of radiation induced effects on indigenously made devices. Bipolar junction transistors of the type 2N2219A (*npn*), 2N3019 (*npn*) and 2N2905A (*pnp*) of Continental Device India Ltd (CDIL) make have been chosen for the present study. These BJTs are exposed to Co^{60} γ - ray, 8 MeV electron and 24 MeV proton to understand the radiation induced degradation mechanism. In addition to this, study of heavy ion induced effects on few imported VLSI devices has also been carried out.

Chapter 1 describes an overview of space radiation environment and the basic theory of interaction of radiation with matter, in general, and with semiconductor in particular. The type of defects generated due to irradiation and the effect of high-energy radiation on BJT are discussed.

Chapter 2 is dedicated to motivation for the present work, a brief survey of the literature available on radiation induced effects in BJT's, the experimental facility and measurement technique used for the present work. Although a large number of reports on radiation induced effects on BJT's are available in the literature, it appears that there is rather little experimental data on the fluence dependence of current gain of the transistor. The main focus of this thesis is to characterize the radiation response of commercial indigenously made BJT's which find applications in space systems. The emphasis is on the degradation of forward current gain of the transistors as a function of accumulated dose/fluence of different radiations. For ^{60}Co γ -irradiation, the facility available at ISRO Satellite Centre, Bangalore has been utilized. 8 MeV electron irradiation and measurements were made utilizing the facility available at Microtron Centre, Mangalore

University. 24 MeV proton irradiation and measurements were made using the Pelletron facility at Nuclear Science Centre, New Delhi. The γ -ray irradiation facility, the particle accelerator facilities and a brief description of measurement methodology are presented in this chapter.

In Chapter 3 the results of the Co^{60} $\tilde{\alpha}$ -ray induced effects on BJT are discussed. Indigenously made transistors of the type 2N2219A (*npn*), 2N3019 (*npn*) and 2N2905A (*pnp*) were exposed to Co^{60} $\tilde{\alpha}$ -ray and on-line measurement of the electrical parameters such as base current (I_B), collector current (I_C) and forward current gain (h_{FE}) of the devices are made using a Semiconductor Parameter Analyzer. Gummel plots also have been obtained for all the devices. The results show that exposure of devices to $\tilde{\alpha}$ -radiation results in significant gain degradation. The results are interpreted in terms of the surface degradation of the oxide passivation layer and displacement damage in the bulk of the semiconductor. The surface degradation has been analyzed using an excess base current model. Gamma-radiation produces bulk damage through the generation of secondary electron. These secondary electrons in turn produce atomic displacements. Displacement related defect and recombination centers contribute to reduction in the minority carrier lifetime leading to current degradation. An estimation of the displacement damage factor has been made as a function of accumulated 0.6 MeV electron fluence by converting the $\tilde{\alpha}$ -dose into 1 rad equivalent electron fluence.

In Chapter 4, the results of the effect of 8 MeV electron irradiation on BJTs of the type 2N2219A (*npn*), 2N3019 (*npn*) and 2N2905A (*pnp*) are discussed. The changes in

electrical parameters due to electron irradiation are measured using the Keithley instruments. The forward current gain of the transistor is measured as a function of accumulated dose of 8 MeV electrons. The results are interpreted in terms of displacement damage produced by the high-energy electrons. Using the Messenger-Spratt equation, the displacement damage factors for each type of the BJTs are calculated. The observation is that both *npn* and *pnp* transistors degrade similarly when exposed to high energy electrons. Further, the defect and recombination centers produced by displacement damage are permanent and do not anneal even at 150° C.

In Chapter 5, the effects of exposure of BJTs to 24 MeV proton beam are analysed. The devices were exposed to 24 MeV proton in the biased condition and *in-situ* measurements of the changes in electrical parameters were made. The results obtained for the BJT 2N2219A (*npn*) are discussed in terms of displacement damage produced by protons in the bulk of the device. The variation of forward current gain and displacement damage factor as a function of accumulated proton fluence indicate that the devices are sensitive to proton radiation. Further, it was observed that the magnitude of the gain degradation due to proton irradiation is much more than that due to γ -ray and electron induced degradation.

To verify the reproducibility of the results, 3-4 transistors of the same batch (date code) have been investigated for all the above mentioned measurements. All the transistors, are found to give roughly identical results.

Chapter 6 describes the theoretical simulation of the variation of displacement damage factor as a function of energy and rad equivalent fluence in bipolar junction transistor for various particulate radiation viz., proton, Si, Cl, Ti, Ni, Br, Ag, I and Au ions. This work is undertaken to formulate a general approach to relate Co^{60} γ -induced effects to particle irradiation effects. This correlation is important because although experiments are carried out for total dose effects using gamma rays, the space environment consists of particulate radiation of different energies and flux. The calculation is based on the experimental data on γ -ray induced gain degradation in a commercial space borne BJT discussed in Chapter 3. The method involves the calculation of γ - ray dose (rad(Si)) equivalent of effective particle fluence. The Linear Energy Transfer (LET) in silicon for different particulate radiation obtained from TRIM (Transport of Ions in Matter) calculation has been used for the conversion of γ -dose into fluence of various particles. The estimation predicts that the displacement damage factor reaches a maximum at the same value of energy which corresponds to maximum LET for all the heavy ions. The maximum value of damage factor marginally decreases with increasing ion fluence for a ion of given energy. These results are expected to be of use to predict the order of the heavy ion induced displacement damage factors in comparison with γ -ray induced effects.

Apart from total dose effects, Single Event Effects (SEE) are also quite important from the point of view of usage of VLSI devices for space application. Detailed understanding of the failure/degradation due to SEE in VLSI devices is quite complex. Nevertheless, an attempt has been made to experimentally characterize some of the VLSI devices for Single Event Upset (SEU) and Single Event Latchup (SEL) when exposed to heavy ions.

The experimental details and test results with respect to SEU, errors, functional failure and SEL of few devices are discussed in **Chapter 7**.

The general conclusions drawn from the present study are summarized in **Chapter 8**. An important observation made in the present study is that the *pnp* transistors are found to degrade as much as the *npn* transistors, a result which is not well established in the literature. The magnitude of current gain degradation is larger due to proton irradiation than that due to gamma and electron irradiation. Indigenous commercial grade bipolar junction transistors degrade in a similar fashion as the devices of the same family from international vendors. As far as the radiation response is concerned, the indigenously made devices are in par with devices of the same family from other vendors. Further, it is inferred that there is a need to establish radiation response data on indigenously made several other important devices which are employed for Indian Space Programme. As this study involves the use of accelerator facility, these investigations require enormous length of time and is expensive also.

List of Publications

Journal Publications

1. *Ionizing Radiation Induced Gain Degradation in Bipolar Transistor.*
S.R. Kulkarni, R. Damle, M. Ravindra and G.R. Joshi.
Journal of Spacecraft Technology, **Vol. 13**, 44 (2003).
2. *Proton and Gamma ray Induced Gain Degradation in Bipolar Transistor.*
S.R.Kulkarni, Asiti Sarma, G.R.Joshi, M.Ravinrda and R.Damle.
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3. *Heavy Ion Testing of VLSI Devices for Single Event Effects.*
S.B. Umesh, G.R. Joshi, B.R. Bhat, M. Ravindra, **S.R. Kulkarni** and R. Damle.
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4. *Simulation of Energy and Fluence Dependence of Heavy Ion Induced Displacement Damage Factor in Bipolar Junction Transistor.*
S.R. Kulkarni, M. Ravindra, G.R. Joshi and R. Damle.
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5. *Gain degradation in BJT- A comparative study between gamma ray and electron induced effects.*
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6. *High-energy heavy ion testing of VLSI devices for single event upsets and latchup.*
S.B.Umesh, **S.R. Kulkarni**, R. Sandhya, G.R.Joshi, R. Damle and M. Ravindra.
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Symposia/Conferences Publications

1. *In-situ study of the effect of 24 MeV proton radiation on commercial bipolar transistors.*
S.R.Kulkarni, R. Damle, B.N.Meera, R.V.Anavekar, N.G.Puttaswamy, Asiti Sarma and B.P. Ajith Kumar.
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2. *Effect of gamma irradiation on the electrical characteristics of bipolar switching transistor.*
S.R. Kulkarni, M. Ravindra, G.R. Joshi and R. Damle.
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S.R. Kulkarni, M. Ravindra, G.R. Joshi, Ganesh, K. Siddappa and R. Damle.
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4. *High Energy Electron Induced Displacement Damage in Bipolar Junction Transistors.*
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5. *Heavy ion testing of VLSI devices for Single Event Effects.*
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