

Modeling and Characterization of Radiation Effects in CMOS Devices and Circuits

KRITIKA ADITYA



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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KRITIKA ADITYA

Department of Electrical Engineering

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*Dedicated to
My Loving Husband
and Parents*

Certificate

This is to certify that the thesis entitled “*Modeling and Characterization of Radiation Effects in CMOS Devices and Circuits*”, being submitted by Ms. **Kritika Aditya** to the Indian Institute of Technology Delhi, is worthy of consideration for the award of the degree of **Doctor of Philosophy** in Department of Electrical Engineering and is a record of the original bonafide research work carried out by her. The results presented in the thesis have not been submitted in part or full, to any other University or Institute for the award of any degree or diploma.

I certify that she has pursued the prescribed course of research.

Date:

Prof. Abhisek Dixit

Place:

Associate Professor,

Department of Electrical Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi – 110016

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Date:

Kritika Aditya

Place:

Abstract

Use of commercial off the shelf electronics for space applications, in nuclear power plants as well as in high-energy physics experiments has led to an increase in research for radiation tolerant technologies. The main objective of this thesis is to investigate and study the radiation response of advanced CMOS technologies through TCAD simulation and characterization. In this thesis, first the single event transient effect is studied and analysed at the device level for planar as well as advanced MOS devices using TCAD simulations. The effect of alpha-particle and heavy-ion irradiations on the single event transient (SET) response of silicon on insulator (SOI) technology is evaluated. For this, thickness scaled fully depleted SOI (FD-SOI) and partially depleted SOI (PD-SOI) devices conforming to 0.18 μm technology node are used. With advancements in semiconductor technology, the sensitivity of Integrated Circuits (ICs) to radiation has increased significantly. Inserted oxide FinFET (iFinFET), which is an evolutionary transistor design, provides better electrostatic integrity compared to FinFETs. The iFinFET device architecture can be of interest for low-power space applications due to its improved performance compared to FinFET. In this thesis, the heavy-ion induced SET response of SOI-FinFETs and iFinFETs conforming to 14 nm technology node is analysed using calibrated TCAD simulations. Transient response of SOI-FinFETs and iFinFETs with varying fin widths, gate lengths, and number of inserted oxides under heavy-ion irradiation are compared. At the system level, embedded memories such as SRAM and embedded-DRAM (eDRAM) are extensively used electronic systems operating under harsh environments. Therefore, to analyse the single event upset (SEU) sensitivities of such memory cells, mixed mode TCAD simulation is utilized. First, heavy-ion induced SEUs are evaluated for SRAM bit-cells designed using these FD-SOI and PD-SOI devices conforming to 0.18 μm technology node. Next, as eDRAM has emerged as a high-speed and high-density replacement for SRAM in embedded memory of the mobile electronic systems requiring large on-chip memories, they may prove to be fatal in presence of ionizing particles. Therefore, next in this thesis, the heavy-ion induced SEU sensitivity of eDRAM designed using a SOI-FinFET conforming to 14-nm technology and deep trench (DT) capacitor is evaluated.

When a semiconductor device is exposed to the ionizing radiation for a prolonged time, the device gradually starts degrading due to accumulation of oxide trapped charges. The degradation in electrical performance of these semiconductor devices under radiation is collectively referred to as total ionizing dose (TID) effect. In this thesis, the deterioration in 180nm n-channel bulk MOSFETs caused by 1 Krad(Si) and 1 Mrad(Si) dose gamma-ray radiations has been investigated. Since TID effect is one of the major concerns for semiconductor devices operated in space, the DC and RF characteristics of advanced devices need to be highly reliable under harsh environmental conditions. Therefore, in this thesis the effect of gamma-ray radiation on DC response of 10-nm bulk FinFETs is demonstrated, where the changes in major DC parameters such as off-state drain current (I_{OFF}), Drain Induced Barrier Lowering (DIBL), threshold voltage (V_{TH}), subthreshold-swing (SS) are reported and analysed for various FinFET geometries. The devices are exposed without any applied bias to a maximum cumulative dose of 42 Mrad(Si). Further, a detailed analysis on the impact of gamma-ray radiation on RF performance of 10-nm bulk FinFETs is reported and an empirical model is developed to demonstrate degradation in the maximum oscillation frequency, f_{MAX} across the device geometry.

सार

वाणिज्यिक इलेक्ट्रॉनिक्स उपकरण के परमाणु ऊर्जा संयंत्रों के साथ-साथ उच्च ऊर्जा भौतिकी प्रयोगों तथा अंतरिक्ष अनुप्रयोगों में उपयोग के कारण विकिरण सहिष्णु प्रौद्योगिकियों के लिए शोध में वृद्धि हुई है। इस थीसिस का मुख्य उद्देश्य टीकैड सिमुलेशन और लक्षण वर्णन के माध्यम से उन्नत सीमौस प्रौद्योगिकियों की विकिरण प्रतिक्रिया की जांच और अध्ययन करना है। इस थीसिस में पहले, एकल घटना क्षणिक (एसइटी) प्रभाव का अध्ययन डिवाइस स्तर पर प्लानर और साथ ही उन्नत सीएमओएस उपकरणों का विश्लेषण टीकैड सिमुलेशन का उपयोग करके किया गया है। सिलिकॉन पर इन्सुलेटर (एसओआइ) तकनीक में अल्फा-कण और हेवी-आयन विकिरणों के कारण एसइटी प्रतिक्रिया के प्रभाव का मूल्यांकन किया गया है। इसके लिए, 0.18 माइक्रोन प्रौद्योगिकी नोड के अनुरूप फुलि डिपलीटिड एसओआइ (एफडी-एसओआइ) और पार्श्वलि डिपलीटिड (पीडी-एसओआइ) उपकरणों का उपयोग किया गया है। अर्धचालक प्रौद्योगिकी में प्रगति के कारण एकीकृत सर्किट (आईसी) के विकिरण की संवेदनशीलता में काफी वृद्धि हुई है। इनसर्टिड ऑक्साइड फ़िनफ़ैट (आईफ़िनफ़ैट), जो कि एक विकासवादी ट्रांजिस्टर डिजाइन है, फ़िनफ़ैट की तुलना में बेहतर इलेक्ट्रोस्टैटिक अखंडता प्रदान करता है। फ़िनफ़ैट की तुलना में बेहतर प्रदर्शन के कारण आईफ़िनफ़ैट डिवाइस आर्किटेक्चर लो-पावर स्पेस एप्लिकेशन के लिए रुचि का हो सकता है। इस थीसिस में, हेवी-आयन प्रेरित एसइटी प्रतिक्रिया का कैलिब्रेटेड टीसीएडी सिमुलेशन का उपयोग करके 14 एनएम प्रौद्योगिकी नोड के अनुरूप बनाए गए एसओआइ-फ़िनफ़ैट और आईफ़िनफ़ैट पर विश्लेषण किया गया है। हेवी-आयन विकिरण के तहत एसओआइ-फ़िनफ़ैट और आईफ़िनफ़ैट की अलग-अलग फिन चौड़ाई, गेट लंबाई और इनसर्टिड ऑक्साइड की संख्या के साथ क्षणिक प्रतिक्रिया की तुलना की गयी है। प्रणाली स्तर पर, एसरैम और एम्बेडेड-डीरैम (ईडीरैम) जैसी एम्बेडेड मेमोरीज़ बड़े पैमाने पर विकिरण वातावरण में काम करने वाले इलेक्ट्रॉनिक सिस्टम में उपयोग होती हैं। इसलिए, इस तरह की मेमोरी सेल्स की सिंगल इवेंट अपसेट (एसईयू) संवेदनशीलता का विश्लेषण करने के लिए, मिश्रित मोड टीकैड सिमुलेशन का उपयोग किया गया है। सबसे पहले, हेवी-आयन प्रेरित एसईयू का मूल्यांकन एसरैम बिट-सेल के लिए किया गया

है जो 0.18 माइक्रोन प्रौद्योगिकी नोड के अनुरूप एफडी-एसओआई और पीडी-एसओआई उपकरणों का उपयोग करके डिज़ाइन की गयी हैं। इसके बाद, क्योंकि ईडीरैम मोबाइल इलेक्ट्रॉनिक प्रणालियों की एम्बेडेड मेमोरी में, जिसमें बड़े-चिप मेमोरी की आवश्यकता होती है, ऐसरैम को प्रतिस्थापन करके एक उच्च-गति और उच्च-घनत्व मेमोरी के रूप में उभरा है, वे आयनकारी कणों की उपस्थिति में घातक साबित हो सकता है। इसलिए, इस थीसिस में आगे, 14-एनएम तकनीक के अनुरूप एसओआई-फ़िनफ़ैट और डीप ट्रैन्च (डीटी) कैपेसिटर का उपयोग करके डिज़ाइन किए गए इडीरैम की हेवी-आयन प्रेरित ऐसईयू संवेदनशीलता का मूल्यांकन किया गया है।

जब एक अर्धचालक उपकरण लंबे समय तक आयनीकृत विकिरण के संपर्क में रहता है, तो ऑक्साइड में फंसे हुए चार्जिज़ के संचय के कारण उपकरण धीरे-धीरे खराब होने लगता है। विकिरण के तहत इन अर्धचालक उपकरणों के विद्युत प्रदर्शन में गिरावट को सामूहिक रूप से टोटल आयनाइज़िंग डोज़ (टीआईडी) प्रभाव के रूप में जाना जाता है। इस थीसिस में 1 किलो रैड(सिलिकन) और 1 मैगा रैड(सिलिकन) गामा-रे विकिरणों की खुराक के कारण 180 एनएम एन-चैनल बल्क मॉसफ़ैट में गिरावट की जांच की गई है। चूंकि टीआईडी प्रभाव अंतरिक्ष में संचालित अर्धचालक उपकरणों के लिए प्रमुख चिंताओं में से एक है, इसलिए उन्नत उपकरण के डीसी और आरएफ प्रतिक्रिया को विकिरण पर्यावरणीय परिस्थितियों में अत्यधिक विश्वसनीय होना चाहिए। इसलिए, इस थीसिस में 10-एनएम बल्क फ़िनफ़ैट की डीसी प्रतिक्रिया पर गामा-रे विकिरण का प्रभाव विभिन्न फ़िनफ़ैट ज्यामितीयों के लिए सूचित और विश्लेषित किया गया है, जहां ऑफ-स्टेट ड्रेन करंट (आइओफ़), डैन इन्डयूस्ड बैरियर लोवरिंग (डिआइबिल), थ्रेशोल्ड वोल्टेज (वीटीएच) और सबथ्रेशोल्ड-स्विंग (ऐसऐस) जैसे प्रमुख डीसी मापदंडों में परिवर्तन होते हैं। उपकरणों को बिना किसी लागू किए गए पूर्वाग्रह के बिना 42 मैगा रैड(सिलिकन) की अधिकतम संचयी खुराक से उजागर किया गया है। इसके अलावा, 10-एनएम बल्क फ़िनफ़ैट के आरएफ़ प्रदर्शन पर गामा-किरण विकिरण के प्रभाव पर एक विस्तृत विश्लेषण की सूचना दी गयी है और विभिन्न डिवाइस ज्यामिति के ऐफ़मैक्स (अधिकतम दोलन आवृत्ति) में गिरावट प्रदर्शित करने के लिए एक अनुभवजन्य मॉडल विकसित किया गया है।

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List of Abbreviations

Abbreviation	Description
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial Off The Shelf
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
TCAD	Technology Computer Aided Design
FET	Field Effect Transistor
SOI	Silicon On Insulator
SEE	Single Event Effect
SEL	Single Event Latch-up
SET	Single Event Transient
SEU	Single Event Upset
TCAD	Technology Computer Aided Design
TID	Total Ionizing Dose
RF	Radio Frequency
SOLT	Short Open Load Thru
FOM	Figure of Merit
