INVESTIGATION OF HYBRID CMOS-NVM CIRCUITS FOR EMERGING APPLICATIONS

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by

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Dedicated to

that ultimate source of creation that resides in everything whatever existed, exits, and will exist in the universe but unknown to most and known to some. It designed me, fabricated me, tested me, motivated me, inspired me, helped me, surprised me, puzzled me, and kept me connected to itself through various means and manifestations.

ॐ

भूर्भुवः स्वः
तत्सवितुर्वरिण्यं
भर्गो देवस्य धीमहि
धियो यो नः प्रचोदयात् ॥

- Rig Veda, Mandala 3, Verse: 3.62.10

“MAY THE ULTIMATE REALITY AND SOURCE OF WISDOM & CREATION, WHICH IS ETERNAL. SUCH POWER ENLIGHTEN OUR INTELLECT AND GUIDE US TO THE TRUTH, KNOWLEDGE, RIGHTEOUSNESS, AND TRUE INTELLIGENCE, I PRAY FOR THIS”

Pieces of Spiritual Wisdom Gained During This Research

- Sometimes just getting an experience is equally important as other achievements/successes like publishing and patenting.

- Our behavior and attitude on difficult days become a part of our research journey and the foundation of our future life. These need to be observed.

- Selfless & sincere efforts towards research have the power to convert our disabilities into abilities.

- Difficulties and adversaries always provide windows for self-improvements.

- Your past deeds cannot be erased off completely. You can not complete anything fully. Trying to settle your current affairs to the best of your capabilities and then move on is the key to keep yourself away from the vicious circle of depression and stagnation.

- A day seems to be very long, but a week or a month passes by very quickly. It happens because of our opposite innate understanding and ability to experience time. Starting every day with new hope and motivation is the key to open new avenues in research.

CERTIFICATE

This is to certify that the thesis entitled **"INVESTIGATION OF HYBRID CMOS-NVM CIRCUITS FOR EMERGING APPLICATIONS"** being submitted by Mr. **ASHWANI KUMAR** for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of bonafide work done by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

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Writing an acknowledgment and expressing my gratitude is like climbing a snow-peaked mountain which is very difficult but beautiful and satisfying at the same time. Earning a doctorate in any field of study is a long process, like growing up as a tree in many uncertainties. But it all starts with a tiny seed of it in our little brain. It is not easy to pinpoint the exact details of sowing the seed and finally coming up as a tree full of fruits. It is not easy to formulate my thoughts to write few words of acknowledgment about the particles and energies in different forms, which directly or indirectly nurtured and provided the suitable ambiance from the start of this journey to become the tree.

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ABSTRACT

INVESTIGATION OF HYBRID CMOS-NVM CIRCUITS FOR EMERGING APPLICATIONS

In the last few decades, the MOSFET has scaled exceptionally well according to Moore's law and has become the cornerstone behind the progress in the field of semiconductor and electronics industry. However, with the emergence of applications such as AI, Big Data, IoT, edge computing, etc., scaling alone is insufficient to address challenging performance requirements. In recent years, emerging nanodevices co-integrated with CMOS as hybrid (CMOS-NVM) circuit solutions have been extensively explored and accepted for various applications.

In this thesis, we investigate multiple "hybrid CMOS-NVM circuits" specifically based on three emerging NVM devices: OTPM, OxRAM, and STT-MRAM. This thesis explores novel architectures (reduced -power, -area, and -complexity), circuits, and optimized programming methodologies for application such as: near/ on-sensor computing, computational ternary content addressable memory (TCAM), and physical unclonable functions (PUF).

सार

उभरते अनुप्रयोगों के लिए हाइब्रिड CMOS-NVM सर्किट का कार्यान्वयन

पिछले कुछ दशकों में, MOSFET ने मूर के नियम के अनुसार बहुत अच्छा विस्तार किया है और अर्धचालक तथा इलेक्ट्रॉनिक्स उद्योग क्षेत्र में प्रगति के पीछे आधारशिला रहा है। हालांकि, एआई, बिग डेटा, आईओटी, एज कंप्यूटिंग, इत्यादि क्षेत्र के उद्भव के कारण, चुनौतीपूर्ण प्रदर्शन आवश्यकताओं को पूरा करने के लिए अकेले स्केलिंग अपर्याप्त है। हाल के वर्षों में, हाइब्रिड (CMOS-NVM) सर्किट समाधानों के रूप में CMOS के साथ सह-एकीकृत उभरते नैनोडेविसेस को विभिन्न अनुप्रयोगों के लिए व्यापक रूप से खोजा और स्वीकार किया गया है।

इस थीसिस में, हम तीन विशिष्ट उभरते NVM उपकरणों जैसे OTPM, OxRAM, और STTMRAM का उपयोग करते हुए कई नए "हाइब्रिड CMOS-NVM सर्किट" की जांच प्रस्तुत करते हैं। यह थीसिस, नियर/ ऑन-सेंसर कंप्यूटिंग, कम्प्यूटेशनल टर्नरी कंटेंट एड्रेसेबल मेमोरी (TCAM), और फिजिकल अनक्लोनेबल फंक्शन्स (PUF) जैसे अनुप्रयोगों के लिए नव आर्किटेक्चर (कम -शक्ति, -क्षेत्र, और -जटिलता), सर्किट, और अनुकूलित प्रोग्रामिंग पद्धतियों की पड़ताल करती है।

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ACRONYMS

AC	Approximate Computing
AI	Artificial Intelligence
ALD	Atomic Layer Deposition
APS	Active Pixel Sensor
BCAM	Binary Content Addressable Memory
BE	Bottom Electrode
BL	Bit Line
CAM	Content Addressable Memory
CC	Current Compliance
CDS	Correlated Double Sampling
CE	Contrast Enhancement
CF	Conductive Filament
CG	Conversion Gain
CIS	CMOS Image Sensor
CMOS	Complementary Metal Oxide Semiconductor
CP	Conductive Path
DC	Direct Current
DE	Distance Error
DPS	Digital Pixel Sensor
DR	Dynamic Range

DRAM	Dynamic Random Access Memory
ET	Error Tolerance
FS	Fast Slow
FD	Floating Diffusion
FF	Fast Fast
GLCM	Gray Level Co-occurance Matrix
GB	Grain Boundary
GF	Gain Factor
HDR	High Dynamic Range
HD	Hamming Distance
HRS	High Resistance State
HR-TEM	High Resolution Transmission Electron Microscopy
IC	Integrated Circuit
IO	Input-Output
IoT	Internet of Things
IMTJ	In-plane Magnetic Tunnel Junction
LRS	Low Resistance State
LSB	Least Significant Bit
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MRAM	Magnetic Random Access Memory
MIM	Metal Insulator Metal
MTJ	Magnetic Tunnel Junction
MA	Magnetic Anisotropy

ML	Match Line
MSB	Most Significant Bit
NVM	Non-volatile Memory
OD	Oxide Diffusion
OTPM	One Time Programmable Memory
OxRAM	Oxide Based Resistive Random Access Memory
PECVD	Plasma Enhanced Chemical Vapour Deposition
PUF	Physical Unclonable Function
PPS	Passive Pixel Sensor
PMTJ	Perpendicular Magnetic Tunnel Junction
PVT	Process Voltage Temperature
PD	Photo Diode
RRAM	Resistive Random Access Memory
ReRAM	Resistive Random Access Memory
RMS	Root Mean Square
SL	Search Line
SA	Sense Amplifier
SF	Slow Fast
SS	Slow Slow
SF	Source Follower
SNR	Signal to Noise Ratio
SHR	Sample Hold Reset
SHS	sample Hold Signal

SRAM	Static Random Access Memory
STT	Spin Transfer Torque
SPICE	Simulation Program with Integrated Circuit Emphasis
SoC	System on Chip
SEM	Scanning Electron Microscope
TCAM	Ternary Content Addressable Memory
TE	Top Electrode
TMR	Tunnel Magnetoresistance Ratio
TT	Typical Typical
WL	Word Line
WVS	Write Voltage Scaling

ABBREVIATIONS

Al	Aluminium
Au	Gold
AlO_x	Aluminium Oxide
CoFeB	Cobalt Iron Boron Magnetic Layer
HfO_x	Hafnium Oxide
MgO	Magnesium Oxide
NiO_x	Nickel Oxide
PCMO	Praseodymium Calcium Manganese oxide
Pt	Platinum
TiN	Titanium Nitride
TBD	Time To Breakdown
TiO_x	Titanium Oxide
TaO_x	Tantalum Oxide
SiO_x	Silicon Oxide
WO_x	Tungsten Oxide

NOTATION

C_{PD}	Photo Diode Capacitance
C_{FD}	Floating Diffusion Capacitance
C-V	Capacitance vs Voltage Characteristic
E_a	Activation Energy
I-V	Current vs Voltage Characteristic
I_{exp}	Exposure (photon) Current at Photo Diode
K_B	Boltzmann's Constant
NM	n-Type MOSFET
PM	p-Type MOSFET
R_P	Parallel State Resistance
R_{AP}	Anti-Parallel State Resistance
T	Temperature
Vo	Oxygen Vacancies
V_{TH}	MOSFET Threshold Voltage
V_{PD}	Photo Diode Node Voltage
V_{FD}	Floating Diffusion Node Voltage