

# **Hot Carrier Reliability Characterization of RF CMOS Circuits and Devices**

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# Hot Carrier Reliability Characterization of RF CMOS Circuits and Devices

by

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*Submitted*

*in fulfilment of the requirements of the degree of Doctor of Philosophy*

*to the*



INDIAN INSTITUTE OF TECHNOLOGY DELHI

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*Dedicated to*  
*My Loving Family*

# Certificate

This is to certify that the thesis entitled “*Hot Carrier Reliability Characterization of RF CMOS Circuits and Devices*”, being submitted by Ms. **Aarti Rathi** 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.

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**Date:**

**Aarti Rathi**

**Place:**

# *Abstract*

An increasing demand for high-speed processing and integration has pushed device engineers to continue with device scaling. But several phenomena are responsible for the degradation of transistor performance, i.e., hot carrier degradation (HCD), bias temperature instability (BTI), time-dependent dielectric breakdown (TDDB), and electromigration (EM). Front-end modules such as Power Amplifiers (PAs), Switches, and Low Noise Amplifiers (LNAs) operate at large RF signals, and the drain terminal experiences a bias of more than twice the power supply voltage ( $V_{DD}$ ) due to large voltage swings. In the case of PAs, depending on their class, the peak of drain voltage could even reach twice or thrice the nominal supply voltage. Such high voltages at the drain terminal of n-channel MOSFETs are known to generate HCD where strong lateral electric field near the drain increases the energy of carriers which leads to impact ionization, trapping of carriers, and interface state generation. These voltage swings that cause a change in degradation mechanisms can be impacted by the varying continuous wave (CW) frequencies. The analysis of reliability behaviour at elevated temperatures also becomes critical to be explored due to increased power dissipation, which reduces the lifetime and performance of devices and circuits. Thus, the temperature dependence on the small and large-signal reliability performance of PA is also required for real-world product front-end applications.

In this thesis, an extensive experimental analysis of hot carrier degradation (HCD) due to DC and large-signal RF stress on an n-channel FET based power amplifier (PA) cell in the sub-7GHz frequency band is done. Through this work, an attempt is made to explore differences in hot carrier degradation mechanisms between DC and RF stress conditions. Generation of defects and their types, i.e., whether oxide or interface traps, are understood using a combination of RF and DC stress conditions. To further observe the impact of large-signal stress for mmWave applications, DC and RF stresses are applied in conducting and non-conducting hot carrier stress modes at a CW of 26.5GHz. It is observed that a change in CW frequency alters the shape of voltage swings which changes the degradation mechanisms and severity of degradation in PA. To

understand different degradation mechanisms, simulation of devices and circuits is also done using the PDK models correlated with experimental data.

As the reliability of the p-FETs is superior to n-FETs, a comparative large-signal reliability investigation is carried out between p-FET PA and n-FET PA for mmWave applications and is found that the RF reliability of the p-FET PA cell is superior to its counterpart n-FET PA cell. Accelerated temperature worsens the reliability performance and thus the large-signal reliability of PA cell for accelerated temperatures is explored. The degradation mechanism for a p-FET based PA involves trapping hot holes in pre-existing traps and the generation of new traps in the oxide due to hot holes. A non-linear relationship between DC and RF figure of merits is investigated for the increasing temperature. For an n-FET based PA, it is found that the unity gain frequencies are also temperature sensitive and show high degradation at elevated temperatures. It is observed that the lifetime is more than ten years when the PA operates at room temperature, which deteriorates as the measurement chuck temperature rises. Further the impact of RF frequency on the DC and large signal reliability performance of a single n-FET based power-amplifier (PA) cell for three different frequency bands, i.e., Ku, K, and Ka band is investigated. The overall performance of the PA cell is superior in the Ka-band but the performance degradation due to reliability mechanisms is also more in this band. It is observed that to achieve superior performance and reliability, a PA cell should be operated at high-frequency bands and the stress power should be kept below P1dB values.

After a detailed reliability study on PA cell, the degradation mechanisms in RF switches for 45nm RFSOI technology under DC and RF stress modes are also investigated in this thesis. A single pole single-throw RF switches using thin and thick gate oxide in series stacked configurations using  $R_{ON}$ . $C_{OFF}$  as a key metric is used for the study. Degradation and breakdown is observed to depend on stress time, DC gate and drain voltages, and RF power. The mechanism causing degradation is studied using the voltage swings at the terminals of the RF switch. RF Switch is observed to exhibit superior reliability under RF 5G mmWave operating conditions. The findings in this work provides an overall picture of large-signal reliability of transceiver for mmWave applications and suggests the region of safe operation to achieve 10-year lifetime.

## सार

उच्च गति प्रसंस्करण और एकीकरण की बढ़ती मांग ने उपकरण अभियंताओं को उपकरण स्केलिंग के साथ जारी रखने के लिए मजबूर किया है। लेकिन ट्रांजिस्टर प्रदर्शन के अवनवीकरण के लिए कई प्रकार की घटनाएं जिम्मेदार हैं, जैसे हॉट कैरियर घटना (एचसीडी), बायस तापमान अस्थिरता (बीटीआई), समयांतरित दियेलेक्ट्रिक ब्रेकडाउन (टीडीडीबी), और इलेक्ट्रोमाइग्रेशन (ईएम)। पावर एम्प्लीफायर (पीए), स्विचेस, और लो नॉइज एम्प्लीफायर (एलएनए) जैसे फ्रंट-एंड मॉड्यूल बड़े आरएफ सिग्नल पर संचालित होते हैं, और ड्रेन टर्मिनल विशेष रूप से बड़ी वोल्टेज स्विंग के कारण पावर सप्लाइ वोल्टेज (वीडीडी) से दोगुना से अधिक बायस अनुभव करता है। पीए के मामले में, उनके क्लास पर निर्भर करता है, ड्रेन वोल्टेज का शीर्ष बिंदु नामक सप्लाइ वोल्टेज के दो या तीन गुना तक जाने सकता है। इस तरह की उच्च वोल्टेज एन-चैनल मॉसफेट्स के ड्रेन टर्मिनल पर एचसीडी उत्पन्न करने के लिए जाने जाते हैं, जहां ड्रेन के आस-पास के सशक्त विद्युत क्षेत्र से धारकों की ऊर्जा को बढ़ाकर यह कैरियर्स के प्रतिक्रिया अपक्षेपण, कैरियर्स को फंसाने और इंटरफेस स्थिति उत्पन्न होती है। ये वोल्टेज स्विंग्स जो अवनवीकरण में परिवर्तन का कारण बनती हैं, उन्हें बदलते चक्रवात (सीडब्ल्यू) फ्रीक्वेंसी द्वारा प्रभावित किया जा सकता है। उच्च तापमान पर विश्वसनीयता व्यवहार का विश्लेषण बढ़े हुए विद्युत विघटन के कारण महत्वपूर्ण हो जाता है, जो उपकरणों और परिपथों के प्रदर्शन और उम्र को कम करता है। इस प्रकार, पीए के छोटे और बड़े सिग्नल विश्वसनीयता प्रदर्शन पर तापमान का अधीनता भी वास्तविक विश्वव्यापी उत्पाद फ्रंट-एंड अनुप्रयोगों के लिए आवश्यक है।"।

इस थीसिस में, एन-चैनल एफईटी आधारित पावर एम्प्लीफायर (पीए) सेल पर डीसी और लार्ज-सिग्नल आरएफ तनाव के कारण हॉट कैरियर घटना (एचसीडी) का व्यापक प्रयोगात्मक विश्लेषण सब-7जीएचजी फ्रीक्वेंसी बैंड में किया गया है। इस काम के माध्यम से, डीसी और आरएफ तनाव की स्थितियों के बीच हॉट कैरियर घटना विकृति यांत्रिकियों के अंतर का पता लगाने का प्रयास किया गया है। आरएफ और डीसी तनाव की स्थितियों के संयोजन का उपयोग करके डिफेक्ट्स की उत्पत्ति

और उनके प्रकार, यानी ऑक्साइड या इंटरफेस ट्रैप्स, को समझा गया है। मिलीमीटरवेव अनुप्रयोगों के लिए लार्ज-सिग्नल तनाव के प्रभाव को और अधिक देखने के लिए, डीसी और आरएफ तनाव एक CW (सतत तरंग) आवृत्ति पर 26.5जीएचजी में निष्पादित किए जाते हैं। यह देखा जाता है कि CW आवृत्ति में परिवर्तन, वोल्टेज स्विंग्स के आकार को बदलता है, जो पीए में अवनवीकरण यांत्रिकियों और घटना के कठोरता को परिवर्तित करता है। विभिन्न अवनवीकरण यांत्रिकियों को समझने के लिए, उपकरणों और सर्किटों के प्रसिद्ध पीडीके (प्रोजेक्ट डिजाइन किट) मॉडल के साथ प्रयोगात्मक डेटा के साथ सिमुलेशन भी किया गया है।

फ़िनफ़ैट पी-एफ़ईटी (p-FETs) की विश्वसनीयता एन-एफ़ईटी (n-FETs) से उत्कृष्ट होने के कारण, एमएमवेव अनुप्रयोगों के लिए पी-एफ़ईटी पीए और एन-एफ़ईटी पीए के बीच एक तुलनात्मक बड़े सिग्नल विश्वसनीयता अनुसंधान किया गया है और पाया गया है कि पी-एफ़ईटी पीए सेल की आरएफ विश्वसनीयता उसके समकक्ष एन-एफ़ईटी पीए सेल से उत्कृष्ट है। त्वरित तापमान विश्वसनीयता प्रदर्शन को बिगाड़ता है और इसलिए त्वरित तापमान के लिए पीए सेल की बड़े सिग्नल विश्वसनीयता की खोज की जाती है। पी-एफ़ईटी पीए पर अवनवीकरण यांत्रिकी में प्रकृति में मौजूद यांत्रिकों में गर्म बिजलियों को फंसाने और गर्म बिजलियों के कारण ऑक्साइड में नई यांत्रिक उत्पन्न होने का संलग्नता होता है। वृद्धि हुए तापमान के लिए डीसी और आरएफ फिगर ऑफ मेरिट के बीच गैर-रैखिक संबंध की खोज की जाती है। एन-एफ़ईटी पीए पर, यूनिटी गेन फ्रीक्वेंसीज़ भी तापमान संवेदक होते हैं और उच्च तापमान पर उनमें उच्च गड़बड़ी दिखाई देती है। देखा गया है कि पीए सेल का उम्र दस से ज्यादा वर्ष होता है जब पीए रूम तापमान पर संचालित होता है, जो मापन चक्रवात तापमान बढ़ने के साथ कम होता है। इसके अलावा, एकल एन-एफ़ईटी आधारित पावर-एम्प्लीफायर (पीए) सेल की डीसी और बड़े सिग्नल विश्वसनीयता प्रदर्शन पर आरएफ आवृत्ति का प्रभाव भी तीन अलग-अलग फ्रीक्वेंसी बैंड, अर्थात्, कु बैंड, के बैंड और का बैंड के लिए जांचा गया है। पीए सेल का समग्र प्रदर्शन का का-बैंड में उत्कृष्ट होता है, लेकिन इस बैंड में विश्वसनीयता यांत्रिकियों के कारण प्रदर्शन दुर्बलता भी अधिक होती है। देखा गया है कि उत्कृष्ट प्रदर्शन और विश्वसनीयता प्राप्त करने के लिए, पीए सेल को उच्च तांत्रिक बैंडों पर संचालित किया जाना चाहिए और तनाव शक्ति को  $P_{1dB}$  मानों से कम रखा जाना चाहिए।

इस थीसिस में, पीए सेल पर विश्वसनीयता के विस्तृत अध्ययन के बाद, 45nm आरएफएसओआई तकनीक के लिए डीसी और आरएफ तनाव मोडों के तहत आरएफ स्विचेस में भी अवनवीकरण यांत्रिकियों का अध्ययन किया जाता है। इस अध्ययन के लिए  $RON.COFF$  को एक मुख्य मापदंड के रूप में उपयोग करते हुए तिप्पणी और मोडनेंचा द्वारा एकजलीय पोल सिंगल-थ्रो आरएफ स्विच का उपयोग किया जाता है। अवनवीकरण और ब्रेकडाउन का अध्ययन देखा गया है कि तनाव समय, डीसी गेट और ड्रेन वोल्टेज, और आरएफ पावर पर निर्भर करता है। अवनवीकरण के कारण होने वाली यांत्रिकता का अध्ययन आरएफ स्विच के टर्मिनल्स पर वोल्टेज स्विंग्स का उपयोग करके किया जाता है। आरएफ स्विच का आरएफ 5जी मिलिमीटरवेव चलने की स्थितियों में उत्कृष्ट विश्वसनीयता प्रदर्शित होता है। इस काम में प्राप्त लाभ से मिलने वाला अंतिम परिणाम है, मिलिमीटरवेव अनुप्रयोगों के लिए ट्रांसीवर की बड़े सिग्नल विश्वसनीयता का सामग्री चित्र प्रदान करता है और 10 वर्षीय जीवनकाल प्राप्त करने के लिए सुरक्षित संचालन क्षेत्र का सुझाव देता है।

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# List of Abbreviations

| Abbreviation  | Description                                       |
|---------------|---|
| <b>BTI</b>    | Bias Temperature Instability                      |
| <b>BSIM</b>   | Berkeley Short-channel IGFET Model                |
| <b>CMOS</b>   | Complementary Metal Oxide Semiconductor           |
| <b>CW</b>     | Continuous Wave                                   |
| <b>DIBL</b>   | Drain Induced Barrier Lowering                    |
| <b>DUT</b>    | Device under Test                                 |
| <b>FET</b>    | Field Effect Transistor                           |
| <b>FOM</b>    | Figure of Merit                                   |
| <b>GSG</b>    | Ground Signal Ground                              |
| <b>HCD</b>    | Hot Carrier Degradation                           |
| <b>HEMT</b>   | High Electron Mobility Transistor                 |
| <b>IC</b>     | Integrated Circuit                                |
| <b>ISS</b>    | Impedance Standard Substrate                      |
| <b>LDD</b>    | Low Doped Drain                                   |
| <b>LNA</b>    | Low Noise Amplifier                               |
| <b>MOSFET</b> | Metal Oxide Semiconductor Field Effect Transistor |
| <b>MSM</b>    | Measure Stress Measure                            |
| <b>NF</b>     | Noise Figure                                      |
| <b>PA</b>     | Power Amplifier                                   |
| <b>PDK</b>    | Process Design Kit                                |
| <b>RF</b>     | Radio Frequency                                   |
| <b>RO</b>     | Ring Oscillator                                   |
| <b>SCE</b>    | Short Channel Effect                              |
| <b>SOC</b>    | System On Chip                                    |
| <b>SOI</b>    | Silicon On Insulator                              |
| <b>SOLT</b>   | Short Open Load Thru                              |
| <b>TDDDB</b>  | Time Dependent Dielectric Breakdown               |
| <b>TRL</b>    | Thru Reflect Load                                 |
| <b>VNA</b>    | Vector Network Analyzer                           |

## List of Values

| Dielectric Constant | Value |
|---------------------|-------|
| Si                  | 11.7  |
| SiO <sub>2</sub>    | 3.9   |
| HfO <sub>2</sub>    | 20    |