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LOW-FREQUENCY NOISE IN ADVANCED MOS DEVICES

by

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PREFACE

The excess noise above the well-known thermal noise and shot noise that shows up at low frequencies, the so-called *low-frequency noise* (other names are 1/*f* noise or flicker noise), has raised questions for a long time and has now become more important than ever. The low-frequency noise generated in the electronic devices is a key problem in analog circuits and systems since it sets a limit on how small signals that can be detected and processed in the circuits. In the early 1990s, the metal-oxide-semiconductor field-effect-transistor (MOSFET) had a channel length of around 0.5 μm and was mainly used in digital electronics. The MOS transistor at that time had a conventional Si channel, SiO_2 gate dielectrics and few advanced features. The tremendous improvements in CMOS performance during the last decade, resulting from continuous advances in the CMOS technology, have stimulated the recent explosion in information and communication technology. Nowadays, MOS transistors are not used only in digital applications but also in a wide range of analog circuits. The low-frequency noise in the CMOS devices has therefore emerged as an important concern. The rapid shrinking of the device dimensions (the smallest gate length is around 30 nm in 2006) is not only a challenging technological problem, the low-frequency noise also increases as the dimensions become smaller with fewer and fewer charge carriers in the active region of the device. It has even been predicted that low-frequency noise will be a problem in digital applications in a few years time.

The CMOS technology has also evolved from the standard Si/SiO_2 material system to more advanced material combinations and new types of device structures. This technology shift has had a pronounced impact on the low-frequency noise properties. The introduction of high-k materials or other

advanced features accompanied with more complex fabrication processes often lead to (more) defects and imperfections in the current path, which can cause a severe degradation of the low-frequency noise performance. A thorough understanding of the low-frequency noise mechanisms, potential noise sources, various noise models, and the impact of technology are thus important for professionals, researchers and students in the electronics field. In particular those working with CMOS device technology and design, characterization and modeling, and circuit design are expected to find great use of this book. The low-frequency noise cannot be completely eliminated, but with careful design of the devices and clever utilization or development of the technology the low-frequency noise can be substantially reduced. Accurate characterization and modeling of the low-frequency noise is not only immensely important for analog circuit designers but also in order to provide an understanding of the noise phenomenon itself. Furthermore, with deeper insights on how the low-frequency noise affects the output noise of a circuit, ways to optimize the circuit for low noise can be sought out.

This book spans from fundamental noise theory via characterization, MOSFET noise models and CMOS technology to address noise in analog/RF circuits. The purpose is both to give the reader an in-depth knowledge of low-frequency noise, while still presented in an easily comprehensible form, and bring together the different pieces all the way from the fundamental theories and physics level to the circuit level. The focus is on MOS devices and technology but the first two chapters about fundamental noise mechanisms and low-frequency noise characterization provide a general background. Other types of FET devices than the MOSFET, bipolar transistors or devices in other materials than Si/SiGe are beyond the scope of this book and are not treated in detail.

This book is structured as follows. In chapter 1, we will give an introduction to noise, describing the fundamental noise sources and basic circuit analysis. The characterization of low-frequency noise is discussed in detail in chapter 2. We will describe the equipment, measurement setups and diagnostic techniques including many useful practical advices. The various theoretical and compact low-frequency ($1/f$) noise models in MOS transistors are treated extensively in chapter 3, providing an in-depth understanding of the low-frequency noise mechanisms and the potential sources of the noise in MOS transistors. We will give an introduction to the MOS transistor and present its noise equivalent circuit. The number and mobility fluctuation noise models are discussed in detail and the $1/f$ noise dependence on device parameters and operating conditions are explained. We also review the most popular compact noise models; the SPICE and Berkeley short channel IGFET (BSIM3) models. In chapter 4, a comprehensive overview of state-of-the-art CMOS technology is presented

together with an exhaustive investigation of the low-frequency noise properties in the various types of advanced CMOS devices. Our presentation includes nanometer scaled devices, strained Si, SiGe, SOI, high-k gate dielectrics, metal gates and finally multiple gates. The book ends with an introduction to noise in analog/RF circuits and describes how the low-frequency noise can affect these circuits. We particularly discuss the voltage controlled oscillator and the upconversion of $1/f$ noise to phase noise as well as the noise properties of mixers and low-noise voltage amplifiers. In order to enhance the understanding of the various aspects of noise fundamentals and the noise implications in advanced CMOS technology, we have composed a number of relevant problems after each chapter. In appendix III a short solution manual is provided.

A reader of this book is assumed to understand fundamental semiconductor physics as well as the principles of CMOS devices at an undergraduate level. Knowledge about noise, CMOS device fabrication or electrical circuits is useful but not necessary. We have mainly followed the conventional notations used in for example Fundamentals of Modern VLSI Devices by Y. Taur & T. K. Ning (Cambridge University Press, Cambridge, 1998). Note that the words low-frequency noise and $1/f$ noise are both frequently used throughout this book, but their meaning is interchangeable for the most part.

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