Preface

Progress in microelectronics over the last several decades has been intimately linked to our ability to accurately measure, model, and predict the physical properties of solid-state electronic devices. This ability is currently endangered by the manufacturing and fundamental limitations of nanometer scale technology, that result in increasing unpredictability in the physical properties of semiconductor devices. Recent years have seen an explosion of interest in Design for Manufacturability (DFM) and in statistical design techniques. This interest is directly attributed to the difficulties of manufacturing integrated circuits in nanometer scale CMOS technologies with high functional and parametric yield.

The scaling of CMOS technologies brought about the increasing magnitude of variability of key parameters affecting the performance of integrated circuits. The large variation can be attributed to several factors. The first is the rise of multiple systematic sources of parameter variability caused by the interaction between the manufacturing process and the design attributes. For example, optical proximity effects cause polysilicon feature sizes to vary depending on the local layout surroundings, while copper wire thickness strongly depends on the local wire density because of chemical-mechanical polishing. The second is that while technology scaling reduces the nominal values of key process parameters, such as effective channel length, our ability to correspondingly improve manufacturing tolerances, such as mask fabrication errors and mask overlay control, is limited. This results in an increase in the relative amount of variation observed. The third, and most profound, reason for the future increase in parametric variability is that technology is approaching the regime of fundamental randomness in the behavior of silicon structures. For example, the shrinking volume of silicon that forms the channel of the MOS transistor will soon contain a small countable number of dopant atoms. Because the placement of these dopant atoms is random, the final number of atoms that end up in the channel of each transistor is a random variable. Thus, the threshold voltage of the transistor, which is determined by the number

of dopant atoms, will also exhibit significant variation, eventually leading to variation in circuit-level performances, such as delay and power.

This book presents an overview of the methods that need to be mastered in understanding state-of-the-art Design for Manufacturability (DFM) and Statistical Design (SD) methodologies. Broadly, design for manufacturability is a set of techniques that attempt to fix the systematic sources of variability, such as those due to photolithography and CMP. Statistical design, on the other hand, deals with the random sources of variability. Both paradigms must operate within a common framework, and their joint understanding is one of the objectives of this book. The areas of design for manufacturability and statistical design are still being actively developed and an established canon of methods and principles does not yet exist. This book attempts to provide a constructive treatment of the causes of variability, the methods for statistical data characterization, and the techniques for modeling, analysis, and optimization of integrated circuits to improve yield. The objective of such a constructive approach is to formulate a consistent set of methods and principles that allow rigorous statistical design and design for manufacturability from device physics to large-scale circuit optimization.

Writing about relatively new areas like design for manufacturability and statistical design presents its difficulties. The subjects span a wide area between design and manufacturing making it impossible to do justice to the whole area in this one volume. We also limit our discussion to problems directly related to variability, with the realization that the term DFM may be understood to refer to topics that we do not address in this book. Thus, we do not discuss topics related to catastrophic yield modeling due to random defects and particles, and the accompanying issues of critical area, via doubling, wire spreading, and other layout optimization strategies for random yield improvement. These topics have been researched extensively, and there are excellent books on the subject, notably [89] and [204].

Also, with the rapid continuous progress occurring at the time of this writing, it is the authors' sincere hope that many of the issues and problems outlined in this book will shortly be irrelevant *solved problems*. We assume that the reader has had a thorough introduction to integrated circuits design and manufacturing, and that the basics of how one creates an IC from the high level system-oriented view down to the behavior of a single MOSFET are well understood. For a refresher, we would recommend [75] and [5].

The book is organized in four major parts. The first part on *Sources of Variability* contains the three chapters of the book that deal with three major sources of variability: front-end variability impacting devices (Chapter 2), back-end variability impacting metal interconnect (Chapter 3), and environmental variability (Chapter 4). The second part on *Variability Characterization and Analysis* contains two chapters. Chapter 5 discusses the design of test structures for variability characterization. Chapter 6 deals with the statistically sound analysis of the results of measurements that are needed to create rigorous models of variability. The third part is on *Design Techniques*

for Systematic Manufacturability Problems, and deals with techniques of design for manufacturability. Chapter 7 describes the interaction of the design and the lithographic flow, and methods for improving printability. Chapter 8 is devoted to a description of techniques for metal fill required to ensure good planarity of multi-level interconnect structures. The final part on *Statistical Circuit Design* is devoted to statistical design techniques proper: it contains four chapters dealing with the prediction and mitigation of the impact of variability on circuits. Chapter 9 presents strategies for statistical circuit simulation. Chapter 10 discusses the methods for system-level statistical timing analysis using static timing analysis techniques. In Chapter 11, the impact of variability on leakage power consumption is discussed. The final chapter of the book, Chapter 12, is devoted to statistical and robust optimization techniques for improving parametric yield.

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